NASA Contractor Report 3731

Enhancement of the CAVE Computer Code

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ILLUSTRATIONS

SUMMARY

Under contract NAS1-13655, Grumman developed the computer code CAVE (Conduction Analysis via Eigenvalues), a convenient and efficient computer code for predicting two-dimensional temperature histories within thermal protection systems for hypersonic vehicles. NASA report CR-2897 describes fully the CAVE code and its operation.

Under the present contract the capabilities of CAVE have been enhanced by incorporation of the following features into the code:

- Real-gas effects in the aerodynamic heating predictions
- Geometry and aerodynamic heating package for analyses of cone-shaped bodies
- Input option to change from laminar to turbulent heating predictions on leading edges
- Modification to account for reduction in adiabatic wall temperature with increase in leading edge sweep
- Geometry package for two-dimensional scramjet engine sidewall, with an option for heat transfer to external and internal surfaces
- Print-out modification to provide tables of select temperatures for plotting and storage
- Modification to the radiation calculation procedure to eliminate temperature oscillations induced by high heating rates.

This report describes these new features and is an addendum to report CR-2897.

Section 1

INTRODUCTION

The CAVE code (Reference 1), which was developed for LaRC under contract NAS1-13655, predicts the transient temperature response within two-dimensional geometries. It has found application in transient heating studies of thermal protection systems for hypersonic aircraft and cruise missiles. CAVE was designed with the convenience of the user in mind. Usual operation of CAVE requires only such minimal information from the user as material properties, initial temperature distribution, flight trajectory (i.e., altitude, velocity, and angle-of-attack as functions of time in tabular form) and selection of one of the built-in general structural configurations, with overall dimensions and grid network sizes specified via input data. CAVE discretizes the geometry into elements and calculates the capacitances, conduction links, and convective boundary conditions. The transient temperature response of the structure is calculated using a hybrid analytical-numerical technique in which spatial derivatives are replaced by appropriate finite difference representations and the temporal derivatives are retained as ordinary derivatives. The numerical technique, developed under LaRc contract NAS-1-11818 (Reference 2), is inherently stable and permits large time steps through the flight trajectory with attendant savings in computer time.

Under the present contract, the utility and capabilities of CAVE have been enhanced by incorporation of the following features into the code:

- Real-gas effects, which become important for Mach numbers above six, into the aerodynamic heat transfer predictions
- A geometry and aerodynamic heating package for analyses of cone-shaped bodies (Figure 1)
- Geometry package for two-dimensional scramjet engine sidewall, with an option for heat transfer to external and internal surfaces (Figure 2)
- Input option to change from laminar to turbulent heating predictions on leading edges

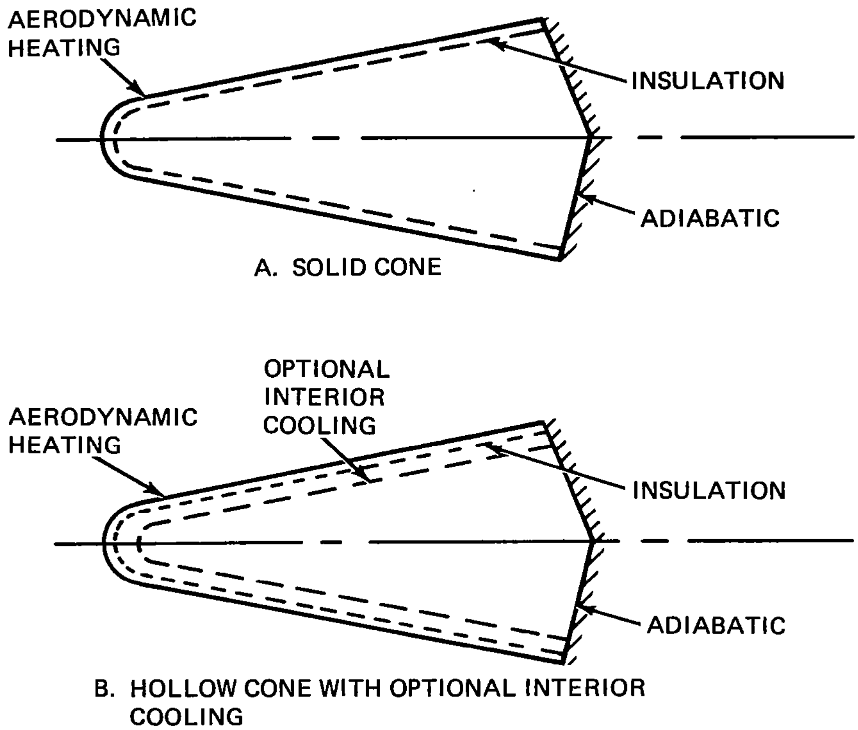

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FIG. 1 BLUNT NOSE CONE GEOMETRY ADDED TO CAVE

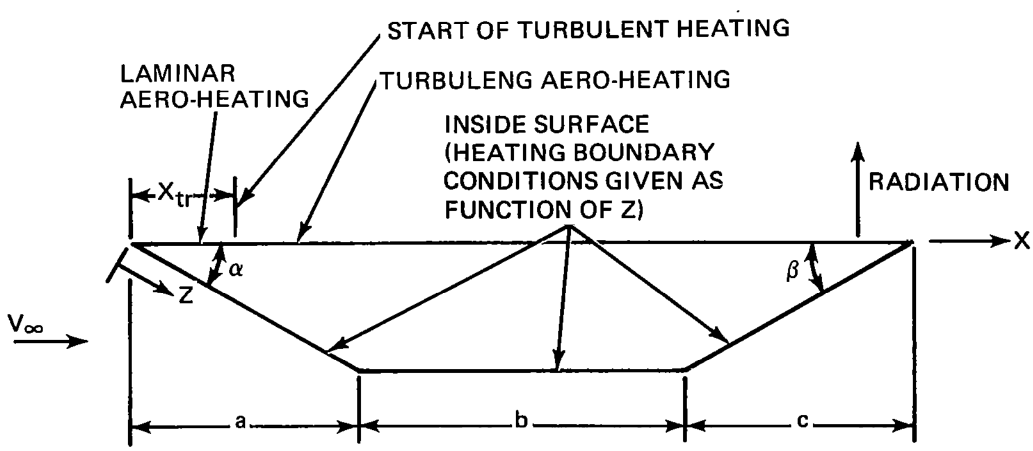

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FIG. 2 SCRAMJET ENGINE SIDEWALL GEOMETRY ADDED TO CAVE

- Modification to account for reduction in adiabatic wall temperature with increase in leading edge sweep
- Print-out modification to provide tables of select temperatures for plotting and storage
- Modification to the radiation calculation procedure to eliminate temperature oscillations induced by high heating rates.

As part of the present contract, a Thermal Analyzer Network Generator was provided to LaRc. This code will be used in conjunction with CAVE3 (Conduction Analysis via Eigenvalues for 3-dimensional Geometries) which was developed under contract NAS1-14643. CAVE3 (Reference 3) is a general computer code for analysis of problems involving any geometry, boundary conditions, and materials. This generality is achieved by requiring the user to establish the thermal network, e.g., node capacitances, conductances between nodes, etc. The Network Generator will significantly reduce the manpower expended creating and debugging models. Basically the Generator utilizes a digitizing tablet for geometry data input, model generation software for calculation of such parameters as node capacitances and conductances, and graphics hardware for displaying the model. A separate report discusses the details and operation of the Network Generator.

The present report is an addendum to the original user's manual for CAVE (Reference 1). Section 2 discusses the modifications that have been incorporated to account for real-gas effects which become important at Mach numbers above 3 or 4. Section 3 discusses the new Blunt-Nosed Cone Geometry; and Section 4 discusses the new Scramjet Engine Side-Wall Geometry. For both geometries, a sample problem is given in addition to the required input data format.

In Section 5, the new option for creating special output files of temperatures and heat transfer coefficients at pre-selected nodes is given. This file can be useful for making quick comparisons and for generation of time-history plots. Section 6 describes the modification that has been added to analyze Leading-Edge Geometry problems with laminar to turbulent flow transition. Section 7 outlines the modifications that have been incorporated into the technique for handling radiation heat transfer. These modifications are directed at eliminating the temperature oscillations that have on occasion been induced by heat heating rates (i.e., rapid changes in temperature) and

large time steps. The Appendix presents flow charts for the new subroutines that have undergone more than trivial modification.

As part of the present contract, the CAVE code was carefully reviewed relative to the reduction in adiabatic wall temperature with increase in leading-edge sweep. Careful examination of the code indicates that the reduction in T_{AW} with increase in sweep angle is accounted for fully and no changes were required.

Mr. James L. Hunt of the High Speed Aerodynamics Division, Langley Research Center, Virginia, served as the NASA technical monitor for the program.

At Grumman, the contract was administered by the Advanced Development office under Mr. Fred Berger, Manager of Advanced Development System Engineering. Dr. Kenneth A. Rathjen was Study Manager and Mr. Henry O. Burk was Programmer. The many helpful discussions with Dr. Robert L. Kosson are gratefully acknowledged.

Section 2

REAL-GAS EFFECTS

For Mach numbers less than 3 or 4, there is virtually no error in calculating the total temperature of a gas via the equation:

$$T_t = T_s \left(1 + \frac{\gamma - 1}{2} M^2\right) \tag{1}$$

where T_t = total temperature, R

T_s = static temperature, R

γ = c_p/c_v

M = Mach number of gas

This equation is valid for gases that satisfy the perfect gas law (Pv = RT), have constant specific heats, and undergo an adiabatic process. For Mach numbers above 4, the temperature dependency of the specific heats introduces errors in the calculation of total temperature via Eq. (1). At Mach 6, the error is approximately 10%, and at Mach 7 it is approximately 20%. This error is on the order of 400 to 500°R, which can be quite significant in the evaluation of thermal protection systems for hypersonic vehicles.

To extend the usefulness of CAVE, the method of calculating the freestream total temperature was modified to the following for Mach numbers greater than three:

1. For the given altitude find, via subroutine ATMOS, the atmospheric ambient pressure P_∞ and temperature T_∞.
2. For the given velocity and ambient temperature calculate the freestream Mach number:

   $M_\infty = V_\infty/(32.2\, \gamma\, R\, T_\infty)^{1/2}$
3. Calculate the dynamic pressure:

   $q_\infty = 0.5\, P_\infty\, \gamma\, M_\infty^2$ psf.

4. Compute pitot pressure:

$$P_{t,2} = 8.92 \times 10^{-4}\, q_{\infty}\, \text{atm}$$

where the constant 8.92×10^{-4} is equal to the product of $14.7 \times 144 \times K$ with $K = 0.53$.

5. Compute freestream enthalpy:

$$h_{\infty} = C_p\, g_c\, J\, T_{\infty} \text{ or}$$

$$h_{\infty} = 0.24 \cdot 25036 \cdot T_{\infty}\ \text{ft}^2/\text{sec}^2$$

6. Compute a normalized total enthalpy:

$$(h/RT_o)_{t,2} = (0.5V^2 + h_{\infty})/843914$$

where the constant 843914 is equal to the product of $g_c RT_o$ with

$R = 53.3 \dfrac{\text{lbf - ft}}{\text{lbf - }^{\circ}\text{R}}$ and $T_o = 491.6$ R = 32 F.

7. Via a table look-up, using $(h/RT_o)_{t,2}$ and $\log_{10} (P_{t,2})$ establish the freestream total temperature $T_{t,2}$.

The table used in Step 7 is to be the first table in the data set of any run. It is provided as part of the code and is referred to as the Standard Table. The format for the table is that required by subroutine NURED1 described in Appendix A of Reference 1. Figure 3 displays the 46 card images of this table.

```
2714          TEMPERATURE AS A FUNC OF LOG10(PRESSURE) & ENTHALPY     00TTOT
       7.6     7.723   8.42    9.12    9.785   10.485  11.191  13.343  14.080  01TTOT
-2.0   1059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   02TTOT
-1.69901059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   03TTOT
-1.39791059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   04TTOT
-1.15491059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   05TTOT
-1.0   1059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   06TTOT
-0.69901059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   07TTOT
-0.39791059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   08TTOT
-0.15491059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   09TTOT
0.0    1059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   10TTOT
0.30 1031059.851080.   1170.   1260.   1350.   1440.   1530.   1800.   1890.   11TTOT
0.60 2061059.851080.   1170.   1260.   1350.   1440.   1530.   1799.301889.9512TTOT
0.845101059.851080.   1170.   1260.   1350.   1440.   1529.   1799.   1889.4913TTOT
1.0    1059.851080.   1170.   1260.   1350.   1440.   1528.751798.761889.1014TTOT
1.30 1031059.851080.   1170.   1259.   1350.   1433.581527.551798.151887.6015TTOT
       16.351  19.362  22.520  25.801  29.4    33.905  37.39   40.2    42.5    16TTOT
-2.0   2160.   2520.   2880.553240.0 3600.   3960.   4185.   4310.   4400.   17TTOT
-1.69902160.   2520.   2881.123242.093609.454003.784210.   4365.   4470.   18TTOT
-1.39792160.   2520.   2881.193242.613616.074018.844260.   4440.   4550.   19TTOT
-1.15492160.   2520.   2881.553244.233620.324036.654300.   4495.   4600.   20TTOT
-1.0   2160.   2520.   2881.803245.2 3622.684047.144320.   4505.334637.4521TTOT
-0.69902160.   2520.   2881.803245.753625.514062.674350.754551.234695.6022TTOT
-0.39792160.   2520.   2881.803246.253627.874076.084379.474595.674754.5523TTOT
-0.15492160.   2520.   2881.803246.273629.294085.194394.524625.084793.7224TTOT
0.0    2160.   2520.   2881.803246.273629.764088.544407.714640.544815.1925TTOT
0.30 1032159.952519.952881.803246.273630.714094.924422.894665.744845.9526TTOT
0.60 2062159.852518.832881.353246.273631.184099.804434.924687.384880.4927TTOT
0.845102159.802518.242881.133246.253631.184101.624441.754701.274901.2128TTOT
1.0    2158.862517.952880.683245.753630.864102.654445.994707.744910.7729TTOT
1.30 1032157.722517.662879.093244.253629.864103.284448.914717.074926.1130TTOT
       45.0    50.0    60.0    70.0    80.0    90.0    100.0   110.0   120.0   31TTOT
-2.0   4490.   4670.   4945.   5170.   5435.   5790.   6325.   6905.   7550.   32TTOT
-1.69904585.   4765.   5065.   5310.   5575.   5925.   6400.   7120.   7665.   33TTOT
-1.39794675.   4870.   5175.   5465.   5745.   6065.   6530.   7195.   99999+934TTOT
-1.15494720.   4945.   5290.   5570.   5865.   6185.   6610.   7260.   99999+935TTOT
-1.0   4760.   4985.   5340.   5645.   5930.   6260.   6690.   7305.   99999+936TTOT
-0.69904820.   5060.   5455.   5800.   6110.   6465.   6845.   7435.   99999+937TTOT
-0.39794915.   5185.   5595.   5945.   6265.   6615.   7025.   7560.   99999+938TTOT
-0.15494975.   5230.   5700.   6065.   6410.   6745.   7180.   7680.   99999+939TTOT
0.0    5000.   5285.   5740.   6145.   6515.   6880.   7295.   99999+999999+940TTOT
0.30 1035035.   5360.   5885.   6310.   6675.   7050.   7480.   99999+999999+941TTOT
0.60 2065070.   5420.   5995.   6460.   6850.   7255.   7580.   99999+999999+942TTOT
0.845105095.   5450.   6095.   6580.   7010.   7425.   99999+999999+999999+943TTOT
1.0    5175.   5505.   6145.   6630.   7085.   7515.   99999+999999+999999+944TTOT
1.30 1035150.   5520.   6200.   6770.   7260.   99999+999999+999999+999999+945TTOT
```

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FIG. 3 TABLE OF $T_{t,2}$ AS A FUNCTION OF $(h/RT_o)_{t,2}$ & LOG $_{10}$ $(P_{t,2})$

Section 3

BLUNT-NOSED CONE GEOMETRY

3.1 DISCUSSION

This subsection presents the blunt-nosed cone geometry that has been incorporated into CAVE and discusses how this geometry is discritized into nodes by the BLUNT2 subroutine. Subsection 3.2 presents the input data format for this geometry and Subsection 3.3 presents a sample problem of a hollow cone.

Figure 4 shows a cross-sectional view of the blunt-nosed cone geometry assumed by subroutine BLUNT2 when it generates a nodal network. The insulating layer can be eliminated by using an input value of zero for TAU. A solid cone is selected by using JGEO = 4, and a hollow cone is selected by using JGEO = 5. Optionally, the hollow cone may be cooled internally. Figure 5 shows the grid network that is generated by BLUNT 2 for solid and hollow cones. Because CAVE is a two-dimensional code, only cones at zero angle-of-attack can be analyzed. Consequently, it is sufficient to show only the upper half of the cone with the understanding that the nodal elements shown are to be rotated about the axis of the cone to produce a body of revolution.

Unlike the cooled leading edge geometry, the cooled cone geometry places no restrictions on the choices for ΔX_i. The thickness of the insulating material is given by TAU and it may equal zero. Notice in Figure 5 that nodes are located on the interface between the insulating material and the main cone material. BLUNT2 assumes that there are equal volumes of the two materials associated with each interface node, i.e., that one half of Δr_3, in this case, is associated with the insulator and the other half with the main material.

The user may elect to have CAVE calculate the convective heat transfer coefficients and adiabatic wall temperatures over the cone or he may supply tabular inputs for them. If the user selects the former option, tabular values for the flight parameters of velocity and altitude (angle-of-attack must equal zero) as functions of time must be supplied. The code uses the axisymmetric method of Fay and Riddell

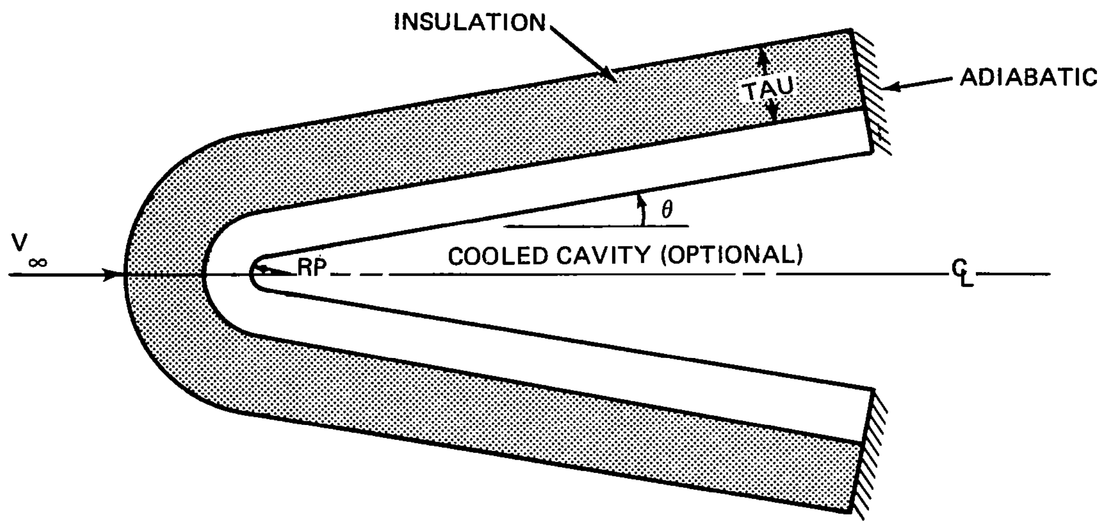

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FIG. 4 BLUNT-NOSED CONE GEOMETRY

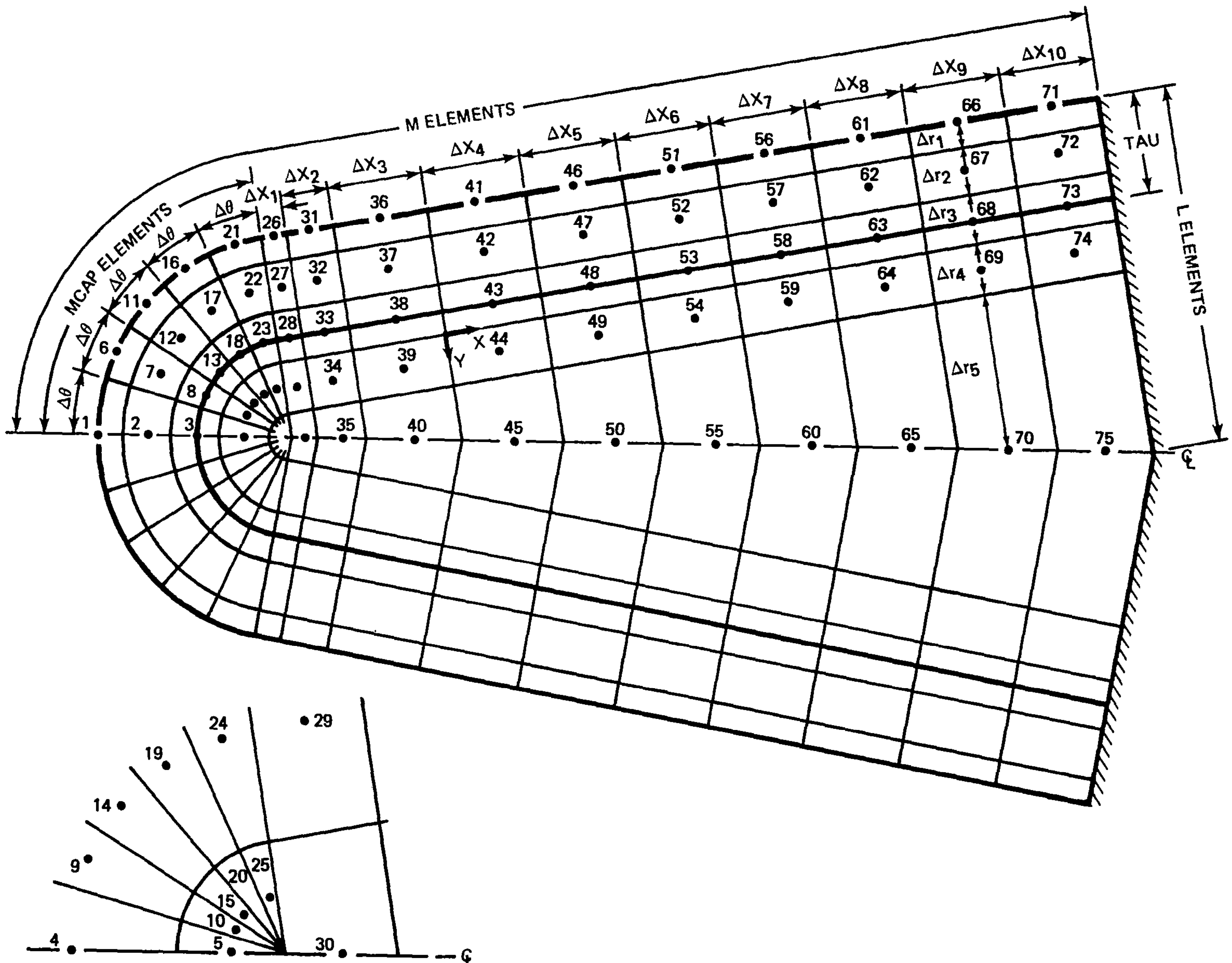

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FIG. 5 NODAL NETWORK FOR SOLID BLUNT-NOSED CONE (SHEET 1 OF 2)

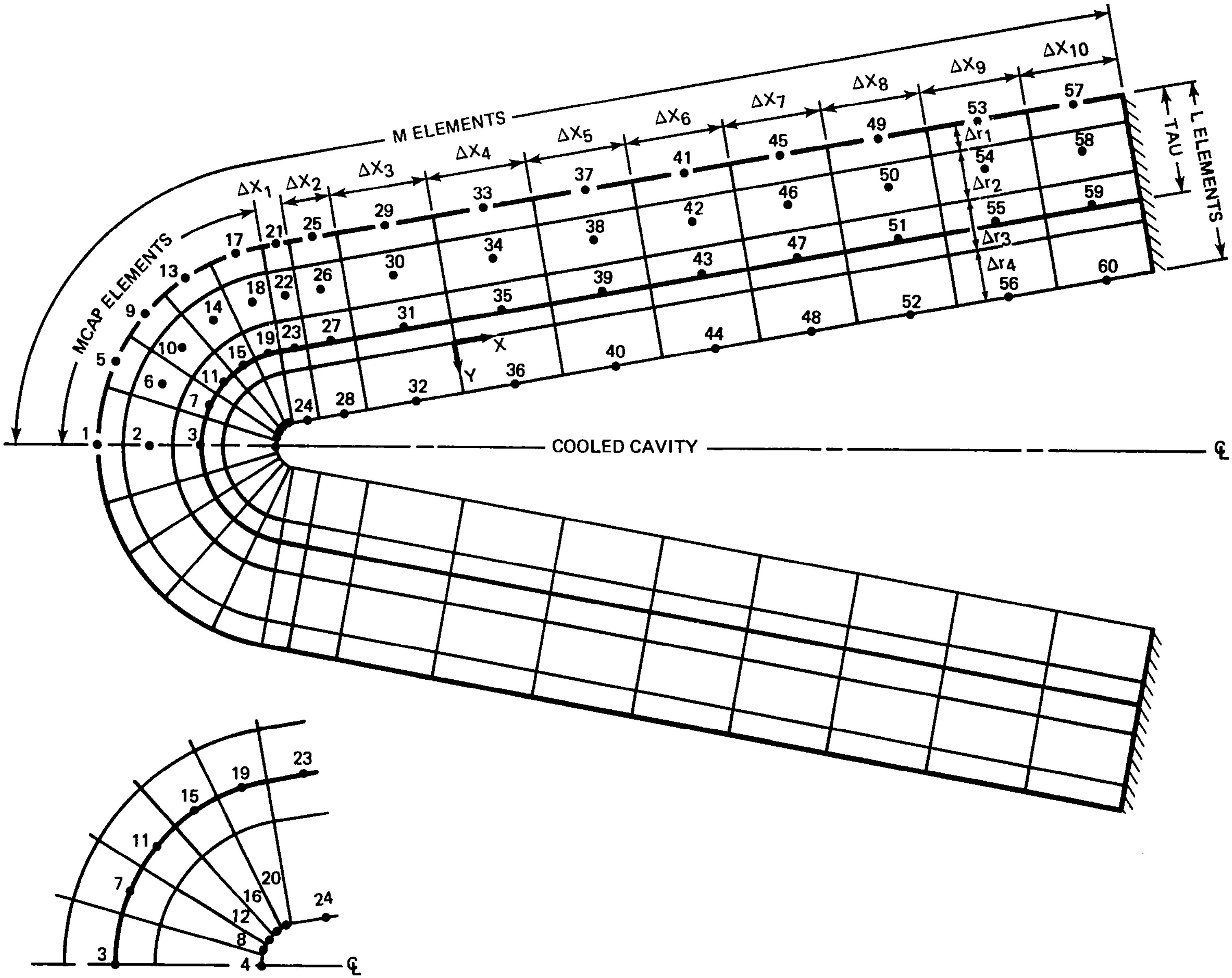

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FIG. 5 NODAL NETWORK FOR HOLLOW BLUNT-NOSED CONE (SHEET 2 OF 2)

(Reference 4) for the stagnation point heating value and Lee's method (Reference 5) for the heat transfer distribution on the spherical nose. Downstream of the spherical nose the Mangler transformation factor is applied to obtain the proper heat transfer coefficients for the cone.

Problems involving increased heating due to local interference heating or other effects such as plume impingement during part of the trajectory can be handled by using the HMODI flags in the same way they are applied in the leading-edge geometry case. It is noted that the surface node elements modified in this way correspond to an entire "ring" around the cone and not a small local surface area on one side of the cone.

In using this multiplier option, it is important to bear in mind that in modifying the convective coefficients, CAVE takes the average of the multiplicative factor at the beginning and end of the time interval and applies it over the entire interval. Therefore, the tables and computing times intervals must be selected with some care whenever step changes are to be simulated. A sample problem in Section 4 of Reference 1 illustrates this point.

3.2 INPUT DATA FORMAT FOR BLUNT-NOSED CONE GEOMETRY

Table Output Card

- ITPRNT (I1)

  ITPRNT = 0: Standard data tables will not be printed

  ITPRNT = 1: Standard data tables will be printed at beginning of printed output.

Standard Tables Cards

The Standard Table is read in so that the program can perform table look-ups of temperature versus enthalpy and pitot pressure. This method is used to obtain TTOT at Mach numbers ≥ 3.0 (thereby accounting for real gas effects). The table must always be read in as part of the input data package whether it will be used or not.

The input format for this table is described in the section dealing with Subroutine NURED, given in Appendix D, Sheet D-1 of Reference 1.

- Table 1 contains: (46 cards)

  TTOT (R) as a function of $\left(\frac{H}{RT_o}\right)_{t,2}$

  (Arg. 1) and Log_{10} $(P_{t,2})$ (Arg. 2), where $P_{t,2}$ is the pitot pressure (in atmospheres)

- Blank Card (signifies end of standard tables).

This table is provided as part of the computer deck.

<u>Indexes Card</u>

- JGEO, L, M, NE (415)

JGEO	=	4 (selects solid cone geometry)
	=	5 (selects hollow cone geometry)
L	=	number of elements through the material (may be an even integer or odd integer)
M	=	number of elements along top surface of cone
NE	=	number of dominant eigenvalues to be used in solution (e.g., a typical number is 5).

<u>Title Card</u>

- Run identification, comments, etc. (8A10)

<u>Radiation Card</u>

- EPS1, TBG1 (2F10.5)

EPS1	=	emissivity of surface
TBG1	=	background radiation temperature, R.

<u>Material Properties Cards</u>

• MAT		(I5)
• NMAT1, RHO1, CONAV1, CPAV1		(I10,3F10.5)
• TMAT1(1), TMAT1(2), . . . , TMAT1 (NMAT1)	omit	(8E10.0)
• CONDT1(1), CONDT1(2), ... , CONDT1 (NAMT1)	if	(8E10.0)
• CPT1(1), CPT1(2), ... , CPT1 (NMAT1)	NMAT1=0	(8E10.0)

(If MAT = 2 include the cards:)

- NMAT2, RHO2, CONAV2, CPAV2 (I10.0,3F10.5)
- TMAT2(1), TMAT2(2), ..., TMAT2 (NMAT2) — omit if NMAT2=0 (8E10.0)
- CONDT2(1), CONDT2(2), ..., CONDT2 (NMAT2) — omit if NMAT2=0 (8E10.0)
- CPT2(1), CPT2(2), ..., CPT2 (NMAT2) — omit if NMAT2=0 (8E10.0)

MAT	=	number of materials (1 or 2)
NMAT1	=	number of entries in properties table (maximum of 10). NMAT1 = 0 for constant properties
RHO1	=	density of material 1, lbm/cu-ft
CONAV1	=	average thermal conductivity of material 1 (used when NMAT1 = 0), Btu/ft-sec-°R
CPAV1	=	average specific heat of material 1 (used when NMAT1 = 0), Btu/lbm-°R
TMAT1(1)	=	temperatures in thermal properties table for which CONDT1 (I) and CPT1 (I) are given; I = 1, 2, ..., NMAT1, °R
CONDT1 (I)	=	thermal conductivity of material 1 at temperature TMAT1 (I), Btu/ft-sec-°R
CPT1 (I)	=	specific heat of material 1 at temperature TMAT1 (I), Btu/lbm-°R

NMAT2, RHO2, CONAV2, etc., same as NMAT1, RHO1, CONAV1, etc., except applied to material 2

Detail Geometry Cards

- MCAP, THETA (I10,F10.5)
- DELX(1), DELX(2), DELX(3), ..., DELX(MM) (8F10.5)
- DELR(1), DELR(2), DELR(3), ..., DELR(L) (8F10.5)
- TAU (F10.5)
- RP, HCOOL, TCOOL (3F10.5)

(omit this card when GEO = 4)

MCAP	=	number of elements into which nose of cone is subdivided (must be an even integer)
THETA	=	wedge half angle of cone, in large
DELX(I)	=	spatial increments in x direction I=1, 2, ..., MM (where MM = M - MCAP), ft

TAU	=	thickness of material 1, ft (when considering only one material, TAU = 0)
RP	=	radius of nose coolant passage, ft
HCOOL	=	convective heat transfer coefficient inside one coolant passage, Btu/ft^2-sec- R
TCOOL	=	cone coolant temperature, R

Initial Temperature Cards

- KODE, I, T(I), II, JJ (2I5, E10.0,2I5)
- ...
- ...
- ...
- 11100 (indicates end of initial temperature cards) (I5)

KODE	=	0 or blank
I	=	node number
T(I)	=	node initial temperature, R
II and JJ	=	the node number is incremented by the spacing JJ until the limit II is reached. Each node so specified is assigned the same temperature.

Special Output File Card(s)

- NPLOTS, ITCODE (2I4)
- NODNUM(1), NODNUM(2), ..., NODNUM (NPLOTS) (omit if NPLOTS = 0)

NPLOTS	=	total number of nodes to be placed in special output file
ITCODE	=	1 if node temperatures are to be stored in R
	=	2 if node temperatures are to be stored in K
NODNUM(I)	=	node number of temperature to be stored I = 1, 2, ... NPLOTS.

Boundary Condition Cards

Two options exist: 1) the user inputs the flight trajectory and the code calculates the convective boundary conditions along the top surface of the cone and 2) the user inputs directly the convective heat transfer coefficient and adiabatic temperature as functions of time and distance.

OPTION 1. FLIGHT TRAJECTORY SPECIFIED

- REFX, CODEX, HMODI (3E10.0)
- GAM, RGAS, PR (3E10.0)
- NTRAJ (I10)
- TIMTAB(1), TIMTAB(2), ..., TIMTAB (NTRAJ) (8E10.0)
- ALTTAB(2), ALTTAB(2), ..., ALTTAB (NTRAJ) (8E10.0)
- VELTAB(1), VELTAB(2), ..., VELTAB (NTRAJ) (8E10.0)

REFX	=	not applicable to cone geometry
CODEX	=	0 (indicates to code that Option 1 is being exercised)
HMODI	=	nonzero value indicates that a table will be read at the end and used to multiply the convective coefficients
GAM	=	ratio of specific heats of air
RGAS	=	gas constant for air, ft-lbf/lbm-R
PR	=	Prandtl number of air
NTRAJ	=	number of points in trajectory table ($2 \leq \text{NTRAJ} \leq 50$)
TIMTAB(I)	=	time in trajectory table I = 1, NTRAJ, sec
ALTTAB(I)	=	altitude corresponding to time TIMTAB(1), ft
VELTAB(I)	=	velocity corresponding to time TIMTAB(I), ft/sec.

OPTION 2. CONVECTIVE COEFFICIENT AND ADIABATIC WALL TEMPERATURE SPECIFIED

- REFX, CODEX, HMODI (3E10.0)

REFX	=	0. (not applicable to cone geometry)
CODEX	=	-1. (indicates to code that Option 2 is being exercised)
HMODI	=	nonzero value indicates that a table will be read at the end and used to multiply the convective coefficient.

Convective Coefficient & Adiabatic Wall Temperature Tables

Two tables are required. The first gives the convective coefficient as a function of time (argument 1) and distance (argument 2). The second table gives the adiabatic wall temperature as a function of time (argument 1) and distance (argument 2). In setting up these tables. The tables must be followed by a blank card. The specifics on the format for the tables are given in the description of subroutine NURED1 in Appendix A of Reference 1.

The following input data is required for both options:

Time Intervals Cards

- NTIMES (I10)
- TIMES(1), TIMES(2), ... TIMES (NTIMES) (8E10.0)

NTIMES(I) = number of points in time intervals array ($2 \leq$ NTIMES ≤ 50)

TIMES(1) = initial time (usually equals 0.) sec

TIMES(I) = time at which temperature is calculated and printed
I = 2, 3, . . . , NTIMES, sec.

Convective Coefficient Modification Table (omit when HMODI = 0.)

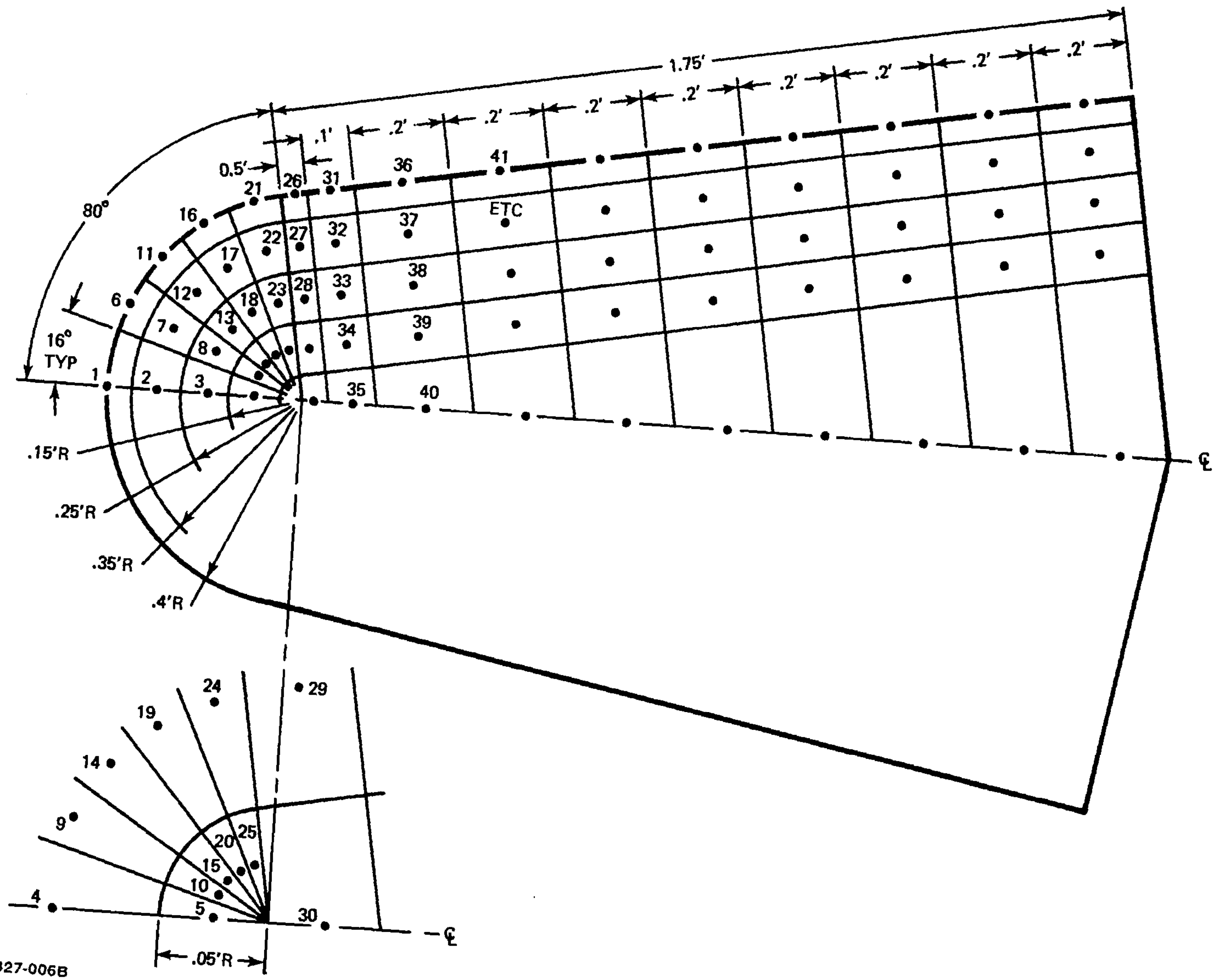
One table is required to modify the convective coefficient on the aerodynamically heated surface. The multiplicative factor is given as a function of time (argument 1) and distance (argument 2). The writeup for subroutine NURED1 (Appendix A of Reference 1) gives the specifics on the format requirements. Follow this table with a blank card; omit the blank card if the table is not read in.

3.3 SAMPLE PROBLEM FOR CONE GEOMETRY

This subsection contains an illustration of the solid blunt-nosed cone geometry considered as a sample problem. Figure 6 shows the grid network. The main features are that it is made of aluminum, has a nose radius of 0.4 ft, and has a length of 1.75 ft. The boundary conditions of h and T_{AW} are uniform and constant with time.

The following pages show listings of the input and output data for this problem. The sequence of the output is:

- Statement regarding storage allocated for S array in main program
- Comment card
- Volumes of nodes computed by CAVE
- Geometry related input data
- Node numbers adjacent to exterior boundary
- material properties
- Boundary conditions table



1827-006B

FIG. 6 GRID LAYOUT FOR SOLID CONE PROBLEM

- Node number location within output array
- Material number assigned to each node. (In this problem there is only one material being used.)
- The capacitance of each node
- The conductance in the x-direction between nodes
- The conductance in the y-direction between nodes
- Initial temperature distribution.

And then the following information is printed for each time interval:

- Average heat transfer coefficients calculated using the h values at the beginning and end of this time interval
- Average heat transfer couplings which include radiation effects, if any
- Average adiabatic wall temperatures for this time interval
- Temperatures at the end of the interval
- Steady-state temperatures for the heat transfer couplings and adiabatic wall temperatures of this interval
- Integrated heat input to each node. This gives the net heat transfer at each boundary node up to the end of this time interval.

(Annotation has been added to the input and output to aid the reader.)

NOTE: ITPRNT, STANDARD TABLE & BLANK CARD NOT SHOWN.

```
J680  L   M   NE
  4   5   15   5
TEST CASE FOR SOLID BLUNT NOSED CONE                          COMMENT CARD
0.0          0.0                                              NO RADIATION
   1                                                          1 MATERIAL
         0          169.     0.04306     0.208                AVERAGE MATERIAL PROPERTIES
         5          10.                                       MCAP, THETA
      0.05          0.1      0.2      0.2      0.2      0.2      0.2      0.2   ΔX'S

        0.2         0.2
      0.05          0.1      0.1      0.1      0.05           ΔR'S
        0.0                                                   TAU
    0    1          500.     75        1                      INITIAL TEMPERATURE
11100
   6    1                                                     SPECIAL OUTPUT FILE OF SELECT NODES, IN R
   1    3   11   24   29   47
        0.0         -1.0               0                      REFX, CODEX, HMODI
0206                 BLUNT NOSED CONE HT DIST.                    00
          0.0     155.                                            01
0.0     .00555  .00555                                            02   TABLE OF H VALUES
0.3     .00555  .00555                                            03   FOR 2 TIME VALUES
.75     .00555  .00555                                            04   & 8 DISTANCE VALUES
1.50    .00555  .00555                                            05
2.25    .00555  .00555                                            06
2.7     .00555  .00555                                            07
0206              BLUNT NOSED CONE TAW DIST.                      00
          0.0     155.                                            01
0.0     1500.   1500.                                             02   TABLE OF TAW VALUES
0.3     1500.   1500.                                             03   FOR 2 TIME VALUES
.75     1500.   1500.                                             04   & 8 DISTANCE VALUES
1.50    1500.   1500.                                             05
2.25    1500.   1500.                                             06
2.7     1500.   1500.                                             07
                          BLANK CARD
          5
0.0          20.        50.       100.       150.             TIME STEP INTERVALS
```

NOTE: THE TIME & DISTANCE VALUES HAVE TO BE THE SAME IN THESE TWO TABLES

1827-007B

SHEET 3.3 INPUT/OUTPUT FOR BLUNT-NOSED SOLID CONE PROBLEM (REFER TO FIG. 4) (SHEET 1 OF 6)

NO. OF ELEMENTS ALONG TOP SURFACE

L

M

NO. OF NODES

NO. OF EIGENVALUES NE

```
                              ++++++++++++++++++++++
                              *                    *
                              *   C A V E  C O D E *
                              *                    *
                              ++++++++++++++++++++++

 15 SURFACE ELEMENTS--   5 ROWS  BY   15 COLUMNS  GIVES   75 ELEMENTS   5 DOMINANT MODES...REQUIRES    2301 WORDS OF MEMORY

ECCNCNOMIZE...REDUCE DIMENSION OF S AND VALUE OF MWORDS FROM  11000 TOWARDS   2591
```

← VALUE REQUIRED FOR THIS PROBLEM

```
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

                  TEST CASE FOR SOLID BLUNT NOSED CONE


VOLUMES OF NCDES
 V(  1)= 0.0017139 V(  2)= 0.0022109 V(  3)= 0.0009939 V(  4)= 0.0002637 V(  5)= 0.0000101 V(  6)= 0.0050090
 V(  7)= 0.0064613 V(  8)= 0.0029046 V(  9)= 0.0007706 V( 10)= 0.0000296 V( 11)= 0.0079160 V( 12)= 0.0102112
 V( 13)= 0.0045904 V( 14)= 0.0012178 V( 15)= 0.0000468 V( 16)= 0.0102097 V( 17)= 0.0131699 V( 18)= 0.0059204
 V( 19)= 0.0015707 V( 20)= 0.0000604 V( 21)= 0.0117124 V( 22)= 0.0151083 V( 23)= 0.0067918 V( 24)= 0.0018019
 V( 25)= 0.0000693 V( 26)= 0.0058732 V( 27)= 0.0047130 V( 28)= 0.0031660 V( 29)= 0.0016191 V( 30)= 0.0004589
 V( 31)= 0.0122196 V( 32)= 0.0098992 V( 33)= 0.0068054 V( 34)= 0.0037115 V( 35)= 0.0013911 V( 36)= 0.0267171
 V( 37)= 0.0220763 V( 38)= 0.0158886 V( 39)= 0.0097009 V( 40)= 0.0050601 V( 41)= 0.0300535 V( 42)= 0.0254127
 V( 43)= 0.0192250 V( 44)= 0.0130373 V( 45)= 0.0083965 V( 46)= 0.0339030 V( 47)= 0.0292622 V( 48)= 0.0230745
 V( 49)= 0.0168868 V( 50)= 0.0122460 V( 51)= 0.0382654 V( 52)= 0.0336246 V( 53)= 0.0274369 V( 54)= 0.0212492
 V( 55)= 0.0166084 V( 56)= 0.0431409 V( 57)= 0.0385001 V( 58)= 0.0323124 V( 59)= 0.0261247 V( 60)= 0.0214839
 V( 61)= 0.0485294 V( 62)= 0.0438886 V( 63)= 0.0377009 V( 64)= 0.0315132 V( 65)= 0.0268724 V( 66)= 0.0544308
 V( 67)= 0.0497901 V( 68)= 0.0436023 V( 69)= 0.0374147 V( 70)= 0.0327739 V( 71)= 0.0608454 V( 72)= 0.0562046
 V( 73)= 0.0500169 V( 74)= 0.0438292 V( 75)= 0.0391884 V(
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

VOLUME OF NODES CALCULATED BY CAVE

```
                                B L U N T   N C S E D   C C N E   P R O B L E M

                                          NOSE RADIUS= 0.4000E+00 FT
                              LENGTH OF CCNE SECTION= 0.1750E+01 FT
                                               THETA= 0.1000E+02 DEG
                                                 TAU= 0.0        FT
                                          EMISSIVITY= 0.0
                            RADIATICN BACKGROUND T= 0.0          DEG.R

     THE EXTERIOR BOUNDARY NODES ARE
   1    6   11   16   21   26   31   36   41   46   51   56   61   66   71

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                                  M A T E R I A L   P R O P E R T I E S

    MATERIAL 1     RHO=169.00 LBM/CU-FT     K=0.04306 BTU/SEC-FT-DEG.R     CP=0.2080 BTU/LBM-DEG.R

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

CONSTANT MATERIAL PROPERTIES

1827-008B

SHEET 3.3 INPUT/OUTPUT DATA FOR BLUNT-NOSED SOLID CONE PROBLEM (REFER TO FIG 4) (SHEET 2 OF 6)

T A B L E S

TABLES 2 AND 3 GIVE H AND TAW FOR EXTERIOR BOUNDARY NODES OF CONE

2 6 BLUNT NOSED CONE HT DIST.

0.0	0.0	0.1550E+03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.5550E-02	0.5550E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.3000E+00	0.5550E-02	0.5550E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.7500E+00	0.5550E-02	0.5550E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.1530E+01	0.5550E-02	0.5550E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.2250E+01	0.5550E-02	0.5550E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.2700E+01	0.5550E-02	0.5550E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLES READ IN FOR h & TAW

2 6 BLUNT NOSED CONE TAW DIST.

0.0	0.0	0.1550E+03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.1500E+04	0.1500E+04	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.3000E+00	0.1500E+04	0.1500E+04	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.7500E+00	0.1500E+04	0.1500E+04	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.1500E+01	0.1500E+04	0.1500E+04	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.2250E+01	0.1500E+04	0.1500E+04	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.2700E+01	0.1500E+04	0.1500E+04	0.0	0.0	0.0	0.0	0.0	0.0	0.0

0 0

++

N O D A L N E T W O R K

NODE NUMBERS

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	1.0	6.0	11.0	16.0	21.0	26.0	31.0	36.0	41.0	46.0
2	2.0	7.0	12.0	17.0	22.0	27.0	32.0	37.0	42.0	47.0
3	3.0	8.0	13.0	18.0	23.0	28.0	33.0	38.0	43.0	48.0
4	4.0	9.0	14.0	19.0	24.0	29.0	34.0	39.0	44.0	49.0
5	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0

ROW / COL	11	12	13	14	15
1	51.0	56.0	61.0	66.0	71.0
2	52.0	57.0	62.0	67.0	72.0
3	53.0	58.0	63.0	68.0	73.0
4	54.0	59.0	64.0	69.0	74.0
5	55.0	60.0	65.0	70.0	75.0

MATERIAL NUMBER AT EACH NODE

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

ROW / COL	11	12	13	14	15
1	1.0	1.0	1.0	1.0	1.0
2	1.0	1.0	1.0	1.0	1.0
3	1.0	1.0	1.0	1.0	1.0
4	1.0	1.0	1.0	1.0	1.0
5	1.0	1.0	1.0	1.0	1.0

ONE MATERIAL THROUGHOUT

CAPACITANCE AT EACH NODE

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	0.602E-01	0.176E+00	0.278E+00	0.359E+00	0.412E+00	0.206E+00	0.430E+00	0.939E+00	0.106E+01	0.119E+01
2	0.777E-01	0.227E+00	0.359E+00	0.463E+00	0.531E+00	0.166E+00	0.348E+00	0.776E+00	0.893E+00	0.103E+01
3	0.349E-01	0.102E+00	0.161E+00	0.208E+00	0.239E+00	0.111E+00	0.239E+00	0.559E+00	0.676E+00	0.811E+00
4	0.927E-02	0.271E-01	0.428E-01	0.552E-01	0.633E-01	0.569E-01	0.130E+00	0.341E+00	0.458E+00	0.594E+00
5	0.356E-03	0.104E-02	0.165E-02	0.212E-02	0.244E-02	0.161E-01	0.489E-01	0.178E+00	0.295E+00	0.430E+00

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SHEET 3.3 INPUT/OUTPUT DATA FOR BLUNT-NOSED SOLID CONE PROBLEM (REFER TO FIG. 4) (SHEET 3 OF 6)

ROW / COL	11	12	13	14	15
1	0.135E+01	0.152E+01	0.171E+01	0.191E+01	0.214E+01
2	0.118E+01	0.135E+01	0.154E+01	0.175E+01	0.198E+01
3	0.964E+00	0.114E+01	0.133E+01	0.153E+01	0.176E+01
4	0.747E+00	0.918E+00	0.111E+01	0.132E+01	0.154E+01
5	0.584E+00	0.755E+00	0.945E+00	0.115E+01	0.138E+01

CONDUCTANCE IN X-DIRECTION.

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	0.265E-01	0.190E-01	0.307E-01	0.399E-01	0.100E+00	0.686E-01	0.709E-01	0.756E-01	0.819E-01	0.881E-01
2	0.529E-01	0.379E-01	0.615E-01	0.798E-01	0.156E+00	0.110E+00	0.587E-01	0.482E-01	0.529E-01	0.576E-01
3	0.529E-01	0.379E-01	0.615E-01	0.798E-01	0.126E+00	0.749E-01	0.410E-01	0.348E-01	0.395E-01	0.442E-01
4	0.529E-01	0.379E-01	0.615E-01	0.798E-01	0.801E-01	0.394E-01	0.232E-01	0.215E-01	0.262E-01	0.309E-01
5	0.265E-01	0.190E-01	0.307E-01	0.399E-01	0.191E-04	0.300E-02	0.209E-02	0.215E-02	0.274E-02	0.333E-02

ROW / COL	11	12	13	14	15
1	0.944E-01	0.101E+00	0.107E+00	0.113E+00	0.0
2	0.623E-01	0.670E-01	0.717E-01	0.764E-01	0.0
3	0.489E-01	0.536E-01	0.583E-01	0.630E-01	0.0
4	0.356E-01	0.403E-01	0.450E-01	0.497E-01	0.0
5	0.392E-02	0.450E-02	0.509E-02	0.568E-02	0.0

ZERO VALUES BECAUSE THERE ARE NO NODES TO THE RIGHT OF THESE

CONDUCTANCE IN Y-DIRECTION

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	0.126E-01	0.107E+00	0.170E+00	0.219E+00	0.251E+00	0.469E-01	0.973E-01	0.209E+00	0.228E+00	0.247E+00
2	0.629E-02	0.537E-01	0.849E-01	0.109E+00	0.126E+00	0.335E-01	0.705E-01	0.155E+00	0.174E+00	0.193E+00
3	0.210E-02	0.179E-01	0.283E-01	0.365E-01	0.419E-01	0.198E-01	0.433E-01	0.101E+00	0.120E+00	0.139E+00
4	0.349E-03	0.298E-02	0.472E-02	0.608E-02	0.698E-02	0.105E-01	0.263E-01	0.725E-01	0.984E-01	0.124E+00
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW / COL	11	12	13	14	15
1	0.265E+00	0.284E+00	0.303E+00	0.322E+00	0.341E+00
2	0.212E+00	0.231E+00	0.250E+00	0.269E+00	0.287E+00
3	0.158E+00	0.177E+00	0.196E+00	0.215E+00	0.234E+00
4	0.149E+00	0.175E+00	0.200E+00	0.225E+00	0.250E+00
5	0.0	0.0	0.0	0.0	0.0

ZERO VALUES BECAUSE THERE ARE NO NODES BELOW THESE

INITIAL TEMPERATURE DISTRIBUTICN DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
2	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
3	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
4	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
5	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0

ROW / COL	11	12	13	14	15
1	500.0	500.0	500.0	500.0	500.0
2	500.0	500.0	500.0	500.0	500.0
3	500.0	500.0	500.0	500.0	500.0
4	500.0	500.0	500.0	500.0	500.0
5	500.0	500.0	500.0	500.0	500.0

++

1827-010B

SHEET 3.3 INPUT/OUTPUT DATA FOR BLUNT-NOSED SOLID CONE PROBLEM (REFER TO FIG. 4) (SHEET 4 OF 6)

****

***** T I M E = 0.2000E+02 S E C O N D S *****

AVERAGE HEAT TRANSFER COEFFICIENTS BTU/SEC-FT**2-DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW / COL	11	12	13	14	15
1	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02
2	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0

AVERAGE HEAT TRANSFER COUPLINGS BTU/SEC-DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	0.216E-03	0.632E-03	0.598E-03	0.129E-02	0.148E-02	0.694E-03	0.143E-02	0.305E-02	0.329E-02	0.353E-02
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW / COL	11	12	13	14	15
1	0.378E-02	0.402E-02	0.426E-02	0.450E-02	0.475E-02
2	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0

AVERAGE ADIABATIC WALL TEMPERATURE DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW / COL	11	12	13	14	15
1	1500.0	1500.0	1500.0	1500.0	1500.0
2	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0

1827-011B

SHEET 3.3 INPUT/OUTPUT DATA FOR BLUNT-NOSED SOLID CONE PROBLEM (REFER TO FIG. 4) (SHEET 5 OF 6)

TEMPERATURES AT THIS TIME DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	529.1	527.0	526.6	526.8	527.6	529.8	531.2	531.2	530.4	529.6
2	522.3	522.7	522.7	522.8	523.1	522.8	522.7	521.9	520.7	519.7
3	519.0	519.4	519.6	519.5	519.1	518.0	516.7	514.8	513.0	511.7
4	517.0	517.1	517.1	516.7	516.1	514.7	512.5	509.5	507.1	505.4
5	516.3	516.3	516.3	516.2	516.1	512.4	510.4	506.9	504.2	502.5

ROW / COL	11	12	13	14	15
1	528.8	527.9	527.0	526.4	526.1
2	518.8	517.8	516.8	516.2	515.8
3	510.5	509.3	508.3	507.6	507.2
4	504.1	502.8	501.6	501.0	500.7
5	501.2	499.8	498.6	498.0	497.8

STEADY-STATE TEMPERATURES FOR THE BOUNDARY CONDITIONS AT THIS TIME DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0
2	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0
3	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0
4	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0
5	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0

ROW / COL	11	12	13	14	15
1	1500.0	1500.0	1500.0	1500.0	1500.0
2	1500.0	1500.0	1500.0	1500.0	1500.0
3	1500.0	1500.0	1500.0	1500.0	1500.0
4	1500.0	1500.0	1500.0	1500.0	1500.0
5	1500.0	1500.0	1500.0	1500.0	1500.0

INTEGRATED HEAT INPUT AT EACH NODE BTU

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	4.2	12.3	19.4	25.1	28.7	13.5	27.8	59.1	63.8	68.6
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW / COL	11	12	13	14	15
1	73.4	78.1	82.9	87.7	92.4
2	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0

***** T I M E = 0.5000E+02 S E C O N D S *****

AVERAGE HEAT TRANSFER COEFFICIENT

ROW / COL	1
1	0.555E-02
2	0.0

1827-012B

SHEET 3.3 INPUT/OUTPUT DATA FOR BLUNT-NOSED SOLID CONE PROBLEM (REFER TO FIG. 4) (SHEET 6 OF 6)

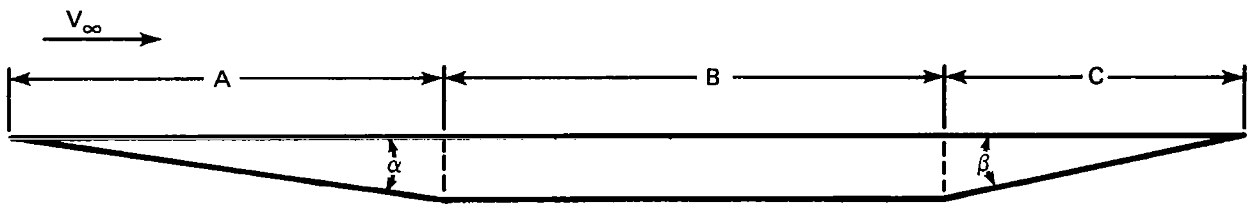
Section 4

SCRAMJET ENGINE SIDE-WALL GEOMETRY

4.1 DISCUSSION

This section describes the scramjet side-wall geometry which has been added to CAVE. An explanation of how the side-wall dimensions are used to construct the nodal network is given, followed by an outline of the input data format.

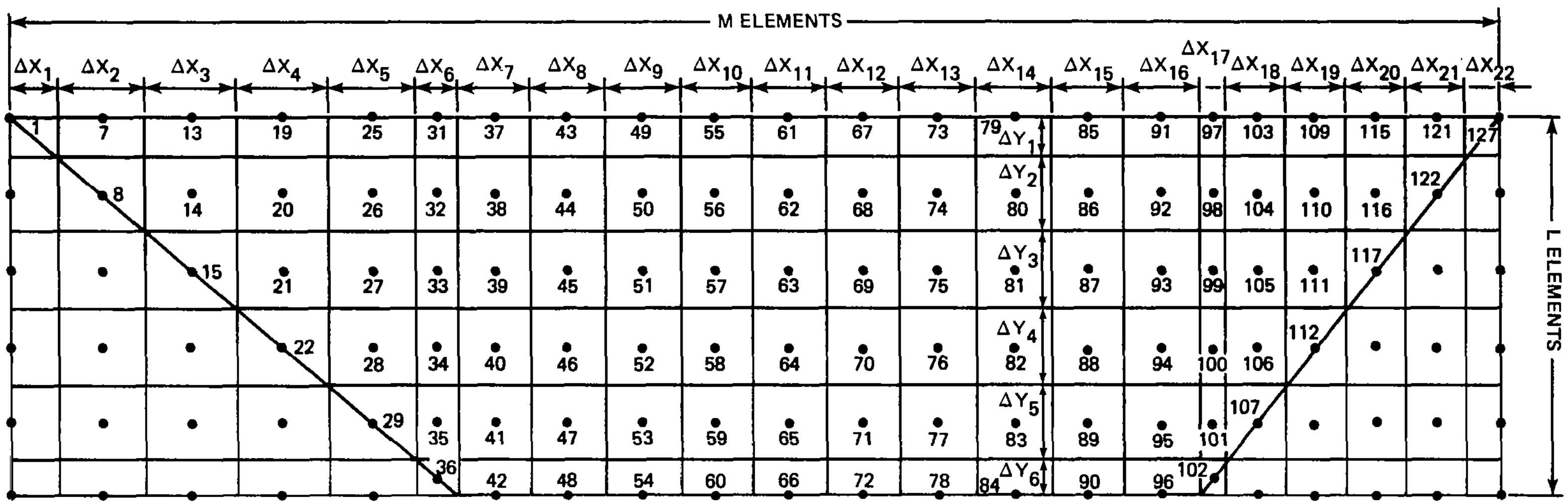
A typical side-wall geometry is shown in Figure 7. The wall is assumed to be of unit depth and to be made of one material with constant properties. To facilitate generation of the nodal network, the side-wall is divided into three principal sections: the forward, center, and aft sections. Figure 7 shows how these divisions are defined, and their lengths are dimensions "A", "B", and "C" respectively. The user must input values for these lengths as well as the angles α and β.



1827-013B

FIG. 7 TWO-DIMENSIONAL SCRAMJET SIDE-WALL ENGINE GEOMETRY

The following discussion refers to Figure 8, which illustrates the arrangement of node elements in the scramjet side-wall as generated by Subroutine WALL2D. One should note that while the elements in the center section are all rectangular, some of the elements on the forward and aft sections are triangular in shape. Spatial increments in the Y direction (ΔY's) must be input by the user. The ΔY's are always constant in the horizontal X direction. Subroutine WALL2D uses the inputs for the dimensions "A" and "C," angles α and β, and the ΔY's to compute the ΔX's for the forward and aft sections in the following manner. The triangular elements have one side forming a part of the wall's lower boundary. The angle of that side with respect to the horizontal is either α or β. Because the ΔY for each element is a known input,



1827-014B

FIG. 8 Nodal Network For Scramjet Side-Wall

all triangular elements of the wall are right triangles, and one of the acute angles is known; the value for ΔX is determined. The ΔX's in the center section are defined by the user, and are required input data.

The number of spacial increments in the X direction (ΔX's) is related to the number of ΔY's the user has specified. The number of ΔX's on the forward and aft sections of the wall are both equal to the number of ΔY's chosen. Thus the total number of ΔX's can be calculated as follows:

Total Number of ΔX's = (No. of ΔX's in Center Section) + 2 x (No. of ΔY's)

Subroutine WALL2D performs a check on the wall dimensions to ensure that the sum of the individual elements truly represents the desired geometry. A discrepancy will cause an error message to be printed and execution of the program will be halted. Processing will be halted if the following relationships are not satisfied.

$$\begin{aligned}
\text{Total Length of Scramjet Wall in the X Direction} &= \underbrace{A + B + C}_{\text{(Input)}} \\
&= \sum_{i=1}^{NDXMID} \underbrace{\Delta X_{i\,\text{(Center Section)}}}_{\text{(Input)}} + \\
&\quad \underbrace{\sum_{i=1}^{NDY} \Delta X_{i\,\text{(Forward Section)}} + \sum_{i=1}^{NDY} \Delta X_{i\,\text{(Aft Section)}}}_{\text{(Computed by WALL2D)}}
\end{aligned}$$

and:

$$A \tan(\alpha) = \sum_{i=1}^{NDY} \Delta Y_i$$

where NDXMID = Number of ΔX's in the Center Section

NDY = Number of ΔY's used through the material

The node numbering system is as shown in Figure 8. Nodes which appear to be located below the wall's lower boundaries in the forward and aft sections are not used in the heat transfer calculations; they are used as an artifice for bookkeeping the node numbers.

For some areas of the scramjet wall, the user may want small nodal elements, such as the regions near the upper left and right corners. Because the ΔX's in these regions are determined by ΔY and α or β, the user must choose an appropriate ΔY to get a ΔX of the right magnitude.

CAVE will permit the user to input a table of convective heat transfer coefficients and adiabatic wall temperatures for the top boundary of the scramjet wall. Alternatively, the user can let CAVE compute these parameters (Subroutine FLATH is used if it were computing H and T_{AW} for a flat plate). If CAVE is to compute h and T_{AW} for the upper wall boundary, trajectory tables are required. In either case, h and T_{AW} for the upper boundary, h and T_{AW} for the lower boundary will be read in as Tables 2 and 3, respectively. When upper and lower boundaries are to be read in as tables, the upper boundary's h and T_{AW} will be in Tables 2 and 3, while the lower boundaries' h and T_{AW} will be in Tables 3 and 5, respectively.

Problems with increased heating due to local interference heating or other effects during part of the trajectory can be handled using the HMODI flags. This option allows modification of the convective heat transfer coefficients along the upper boundary of the wall, and requires the user to input an additional table of heating modifiers.

4.2 INPUT DATA FORMAT FOR SCRAMJET SIDE-WALL GEOMETRY

Table Output Card

- ITPRNT (I1)

  ITPRNT = 0: Standard data tables will not be printed

  ITPRNT = 1: Standard data tables will be printed at beginning of printed output.

Standard Tables Cards

Standard Tables are read in so that the program can perform table look-ups of temperature vs enthalpy and pitot pressure. This method is used to obtain TTOT at Mach numbers ≥ 3.0 (thereby accounting for real gas effects).

The input format for this table is described in the section dealing with Subroutine NURED1, given in Appendix A, Sheet A-1 of Reference 1.

- Table 1 contains: (46 cards)

  TTOT (°R) as a function of $\left(\frac{H}{RT_o}\right)_{t,2}$ (Arg. 1) and Log_{10} ($P_{t,2}$) (Arg. 2),

  where $P_{t,2}$ is the pitot pressure (in atmospheres)
- Blank Card (Signifies end of standard tables).

This table is provided as part of the computer deck and must be read in as part of the input data package whether it will be used or not.

Indexes Card

- JGEO, L, M, NE (4I 5)

JGEO	=	3 (selects Scramjet Side-wall Geometry)
L	=	Number of elements through the material (may be an even integer or an odd integer)
M	=	Number of elements along the top surface of the scramjet side-wall
NE	=	Number of dominant eigenvalues to be used in solution (e.g., a typical number is 5).

Geometry Cards

- A, B, C, ALFA, BETA (refer to Figure 7) (8F10.0)

A	=	Length of forward section of wall
B	=	Length of center section of wall
C	=	Length of aft section of wall
α	=	Angle of wall boundary at front of wall (in degrees)
β	=	Angle of wall boundary at rear of wall (in degrees)

- NDXMID

NDXMID	=	Number of ΔX's in the center section of wall

- DX(1), DX(2), DX(3), ... DX(NDXMID) (8F10.0)

DX(I)	=	Spatial increments in X direction for center section of wall (region of length = B), ft (I = 1, 2, ... NDXMID)

- NDY (I5)

NDY	=	Number of ΔY's in the center section

- DELY(1), DELY(2), DELY(3), ... DELY(NDY) (8F10.0)

  DELY(I) = Spatial increments in Y direction for center section of wall, ft (I = 1, 2, ... NDY).

Title Card

- Run identification, comments, etc. (8A10)

Radiation Card

- EPS1, TBG1 (2F10.5)

  EPS1 = emissivity of surface

  TBG1 = background radiation temperature, R.

Material Properties Cards

- MAT (I5)
- NMAT1, RHO1, CONAV1, CPAV1 (I10,3F10.5)
- TMAT1, TMAT1(2), ..., TMAT1 (NMAT1) } omit (8E10.0)
- CONDT1(1), CONDT1(2), ..., CONDT1 (NMAT1) } if (8E10.0)
- CPT1(1), CPT1(2), ..., CTP1 (NMAT1) } NMAT1=0 (8E10.0)

MAT	=	number of materials = 1
NMAT1	=	number of entires in properties table (maximum of 10). NMAT1 = 0 for constant properties
RHO1	=	density of material 1, lb/cu-ft
CONAV1	=	average thermal conductivity of material 1 (used when NMAT1 = 0), Btu/ft-sec-R
CPAV1	=	average specific heat of material 1 (used when NMAT1 = 0), Btu/lbm-R
TMAT1(I)	=	temperatures in thermal properties table for which CONDT1 (I) and CPT1 (I) are given; I = 1, 2, ..., NMAT1, R
CONDT1 (I)	=	thermal conductivity of materials 1 at temperature TMAT1 (I), Btu/ft-sec-R
CPT1 (I)	=	specific heat of material 1 at temperature TMAT1 (I), Btu/lbm-R

Initial Temperature Cards

- KODE, I, T(I), II, JJ (2I5,E10.0,2I5)
- ...
- ...
- ...
- 11100

KODE	=	0 or blank
I	=	node number
T(I)	=	node initial temperature, R
II and JJ	=	the node number is incremented by the spacing JJ until the limited II is reached. Each node so specified is assigned the same temperature.

Special Output File Card(s)

- NPLOTS, ITCODE (214)
- NODNUM(1), NODNUM(2), ... NODNUM (NPLOTS)
  (Omit if NPLOTS = 0) (20I4)

NPLOTS	=	number of nodes whose data will be written into special output file
ITCODE	=	1 if node temperatures in special file are to be in R
	=	2 if node temperatures in special file are to be in K
NODNUM(I)	=	node number of temperature to be stored I = 1, 2, ... NPLOTS.

Boundary Condition Cards

Two options exist: 1) in the first option, the user inputs the flight trajectory and the code calculates the convective boundary conditions along the top surface of the panel in accordance with the equations presented in Appendix B of Reference 1, and 2) in the second option, the user inputs directly the convective heat transfer coefficient and adiabatic temperature as functions of time and distance.

OPTION 1. FLIGHT TRAJECTORY SPECIFIED

- REFX, CODEX, HMODI (3E10.0)
- GAM, RGAS, PR (3E10.0)

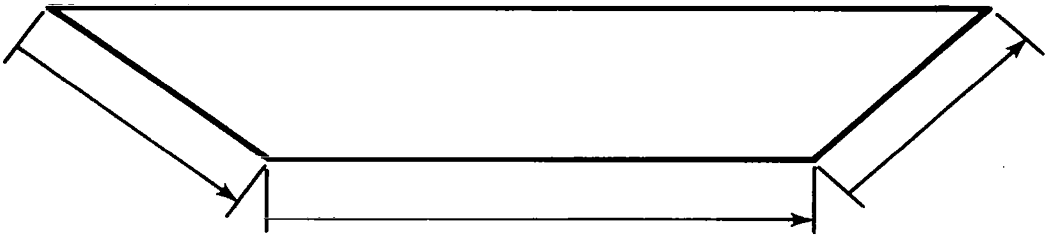
- NTRAJ (I10)
- TIMTAB(1), TIMTAB(2), ..., TIMTAB (NTRAJ) (8E10.0)
- ALTTAB(1), ALTTAB(2), ..., ALTTAB (NTRAJ) (8E10.0)
- VELTAB(1), VELTAB(2), ..., VELTAB (NTRAJ) (8E10.0)
- ALPTAB(1), ALPTAB(2), ..., ALPTAB (NTRAJ) (8E10.0)

REFX	=	effective boundary layer length, e.g, distance from leading edge of scramjet wall
CODEX	=	0. for uniform convective coefficient across top surface; CODEX = 1. for nonuniform convective coefficient (i.e., function of x); CODEX = -1. for tabular input for convective coefficient and adiabatic wall temperature
HMODI	=	nonzero value indicates that a table will be read at the end and used to multiply the convective coefficients
GAM	=	ratio of specific heats of air
RGAS	=	gas constant for air, ft-lbf/lbm-°R
PR	=	Prandtl number of air
NTRAJ	=	number of points in trajectory table ($2 \leq NTRAJ \leq 50$)
TIMTAB(I)	=	time in trajectory table I = 1, NTRAJ, sec
ALTTAB(I)	=	altitude corresponding to time TIMTAB(I), ft
VELTAB(I)	=	velocity corresponding to time TIMTAB(I), ft/sec
ALPTAB(I)	=	angle of attack corresponding to time TIMTAB(I), in degrees.

Convective Coefficient & Adiabatic Wall Temperature Tables

Two tables are required to define the convective coefficient and adiabatic wall temperature along the lower boundaries of the scramjet wall. The first table gives the convective coefficient as a function of time (argument 1) and distance (argument 2) and the second gives the adiabatic wall temperature. The same values must be used for time and distance in both tables. The range of the distance argument must be from the upper left hand corner of the wall to the upper right hand corner as measured along the lower wall boundary, as shown in Figure 9. A description of the rable format can be found in the section on Subroutine NURED in Appendix D of Reference 1.

- Blank Card (signifies end of tables).



1827-015B

FIG. 9 LOWER BOUNDARY LENGTH FOR SCRAMJET WALL

OPTION 2. CONVECTIVE COEFFICIENT & ADIABATIC WALL TEMPERATURE SPECIFIED FOR UPPER & LOWER BOUNDARIES OF SCRAMJET SIDE-WALL

- REFX, CONDEX, HMODI (3E10.0)

REFX	=	effective boundary layer length, e.g., distance from leading edge of side-wall, ft
CODEX	=	-1. (indicates to code that Option 2 is being exercised)
HMODI	=	nonzero value indicates that a table will be read at the end and used to mulitply the convective coefficients.

Convective Coefficient & Adiabatic Wall Temperature Tables

Four tables are required. The first gives the convective coefficient as a function of time (argument 1) and distance (argument 2), for the wall upper boundary. The second table gives the adiabatic wall temperature as a function of time (argument 1) and distance (argument 2), for the wall upper boundary. In setting up these tables, the same values for time and distance must be used in both tables. The range of the distance argument must include the interval REFX to REFX plus the total length of the scramjet wall (i.e., A + B + C). The specifics on the format for the tables are given in the descriptions of subroutine NURED1 in Appendix D of Reference 1.

Similarly, the third and fourth tables should contain convective coefficients and adiabatic wall temperatures for the lower boundary of the wall. Distance must be measured along the lower boundary as shown in Figure 9. The range of the distance argument for the lower boundary must be from zero to $\left(\frac{A}{\cos(\alpha)} + B + \frac{C}{\cos(\beta)}\right)$.

- Blank Card (signifies end of tables).

Time Intervals Cards

- NTIMES (I10)
- NTIMES(1), NTIMES(2), ..., TIMES (NTIMES) (8E10.0)

NTIMES(I) = number of points in time intervals array ($2 \leq$ NTIMES ≤ 50)

TIMES(I) = initial time (usually equals 0.) sec

TIMES(I) = time at which temperature is calculated and printed I = 2, 3, . . . NTIMES, sec.

Convective Coefficient Modification Table (omit when HMODI = 0.)

One table is required to modify the convective coefficient on the aerodynamically heated surface. The multiplicative factor is given as a function of time (argument 1) and distance (argument 2). The writeup for subroutine NURED1 (Appendix D of Reference 1) gives the specifics on the format requirements. Follow this table with a blank card; omit the blank card if the table is not read in.

4.3 SAMPLE PROBLEM FOR SCRAMJET SIDE-WALL GEOMETRY

This subsection contains an illustration of the scramjet side-wall geometry. Figure 8 shows the nodal network. The section has an overall length of 11 ft and a maximum thickness of 0.5 ft. The boundary conditions on the upper wall are calculated by the code using a constant flight profile of 40,000 ft altitude and 3,000 ft/sec velocity. On the bottom surface the convective heat transfer coefficient was input as 0.00555 Btu/sec/ft^2/R and the adiabatic wall temperature as 1,500 R. Both values were input to be constant for the entire time period of interest (200 sec).

The following pages show listings of the input and output data for this problem. The sequence is:

Print-Out of Input Data:

- Standard Table
- Problem related input data.

Print-Out of Output Data:

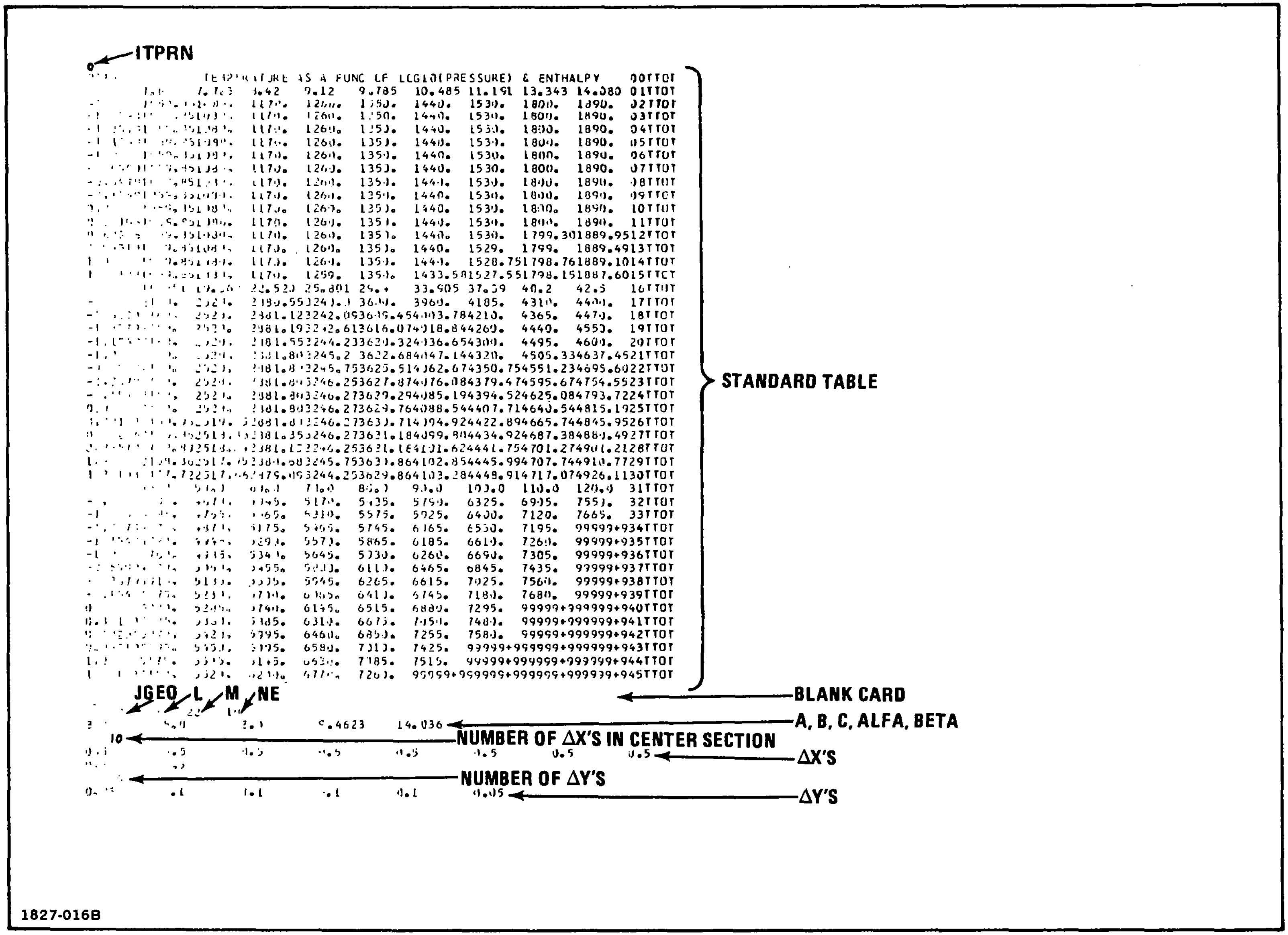
- Geometry data
- ΔX's and ΔY's
- Volumes of nodes

- Statement regarding storage allocated for S array in main program
- Comment card
- Material properties
- Boundary conditions tables
- Node number location within output array
- Material number assigned to each node. (Only one material can be used with this geometry.)
- The capacitance of each node
- The conductance in the x-direction between nodes
- The conductance in the y-direction between nodes
- Initial temperature distribution.

And then the following information is printed for each time interval:

- Flight trajectory parameters, Mach number, altitude, velocity and angle of attack for each time interval
- Average heat transfer coefficients calculated using the h values at the beginning and end of this time interval
- Average heat transfer couplings, which include radiation effects, if any, calculated using the temperatures at the beginning of this time interval
- Average adiabatic wall temperatures for this time interval
- Temperatures at the end of the interval
- Steady-state temperatures for the heat transfer couplings and adiabatic wall temperatures of this interval
- Integrated heat input to each node. This gives the net heat transfer at each boundary node up to the end of this time interval.

(Annotation has been added to the input and output to aid the reader.)



SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 1 OF 11)

```
SCRAMJET WALL GEOMETRY TEST CASE WITH TOP BOUNDARY H AND TAW CALCULATED.   <-- COMMENT CARD
        0.        0.                                                       <-- EPS1, TBG1
   1                                                                       <-- MAT
        0       169.    0.04306      0.219                                 <-- MATERIAL PROPERTIES
        1 500.0         132    1                                           <-- INITIAL TEMPERATURE
11100                                                                      <-- SIGNIFIES END OF INIT TEMP CARDS
  11    1
   1    3   11   24   29   47   82   9?   95   96  100                     ] <-- SPECIAL OUTPUT FILE CARDS
 0.         2.0        0.                                                  <-- REFX, CODEX, HMODI
       1.4        53.3        .65                                          <-- AIR PROPERTIES
        4
        0.          5.          10.         20.
   40000.      40000.      40000.      40000.                              ] <-- FLIGHT TRAJECTORY
    3000.       3000.       3000.       3000.
        0.          0.          0.
1203                  SCRAMJET WALL INNER SURFACE HT DIST.
        0.0      200.
 .0    .00555 .00555
 .0    .00555 .00555
10.2   .00555 .00555                                                       ] <-- LOWER WALL BOUNDARY H AND TAW DISTRIBUTION
1203             TAW    SCRAMJET INNER WALL SURFACE DIST.
        0.0      200.
 .0    1500.   1500.
 .00   1500.   1500.
10.2   1500.   1500.
                                                                           <-- BLANK CARD
        5
 .0       120.        140.        160.        200.                         ] <-- TIME STEP INTERVALS
```

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SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 2 OF 11)

```
INPUT DATA FOR SCRAMJET WALL HEATING

A=       2.00
B=       1.00
C=       2.00
ALFA=    0.10[illegible] RADIANS
ALFA=    5.[illegible] DEGREES
BETA=    0.24497 RADIANS
BETA=    1[illegible] DEGREES
```

PRINT-OUT OF INPUT DATA DESCRIBING SCRAMJET WALL GEOMETRY

```
NUMBER OF DELX'S IN CENTER SECTION =   10

DELX'S INPUT

     0.50      0.50      0.50      0.50      0.50      0.50      0.50      0.50      0.50      0.50
```

LIST OF ΔX'S IN CENTER SECTION OF WALL

```
NUMBER OF DELY'S=    6

DELY'S INPUT

     0.05      0.10      0.10      0.10      0.10      0.05
```

LIST OF ΔY'S

LIST OF ALL ΔX'S – INCLUDES THOSE INPUT FOR CENTER SECTION & THOSE COMPUTED BY CAVE

```
DELX'S FOR WALL.

     0.300     0.600     0.600     0.600     0.500     0.500     0.500     0.500     0.500     0.500
     0.500     0.500     0.500     0.500     0.500     0.500     0.200     0.400     0.400     0.400
     0.400     0.200
```

LIST OF ΔY'S USED IN PROGRAM (SHOULD BE SAME AS ABOVE)

```
DELY'S FOR WALL.

     0.050     0.100     0.100     0.100     0.100     0.050
```

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SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 3 OF 11)

R/COL
C
*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	[illegible]	0.030	[illegible]	0.030	[illegible]	0.015	0.025	0.025	0.025	0.025	0.025	0.025	0.025'	0.025	0.025	0.025
2	0.0	0.030	0.060	0.060	0.060	0.030	0.050	0.050	[illegible]	0.050	0.050	0.050	0.050	0.050	0.050	0.050
3	0.0	0.0	[illegible]	[illegible]	0.060	[illegible]	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
4	0.0	0.0	0.0	[illegible]	[illegible]	[illegible]	0.050	[illegible]	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
5	0.0	0.0	0.0	0.0	[illegible]	[illegible]	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
6	0.0	0.0	0.0	0.0	0.0	[illegible]	0.025	[illegible]	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025

VOLUMES OF NODAL ELEMENTS
COMPUTED BY CAVE

R/COL
C
*

	17	18	19	20	21	22
1	[illegible]	0.020	0.020	0.020	0.020	0.005
2	0.020	0.040	0.040	0.040	0.020	0.0
3	0.020	0.040	0.040	0.020	0.0	0.0
4	0.020	0.040	0.020	0.0	0.0	0.0
5	0.020	0.020	0.0	0.0	0.0	0.0
6	0.005	0.0	0.0	0.0	0.0	0.0

NO OF ELEMENTS ON SCRAMJET
WALL SURFACE BOUNDARIES

L

M

NO. OF NODES

NO. OF EIGEN VALUES

42 SURFACE ELEMENTS-- 6 ROWS BY 22 COLUMNS GIVES 132 ELEMENTS 10 DOMINANT MODES...REQUIRES 6644 WORDS OF MEMORY

ECONOMIZE...REDUCE DIMENSION OF S AND VALUE OF WORDS FROM 11000 TOWARDS 7058

ARRAY SIZE REQUIRED
FOR THIS PROBLEM

++

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SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 4 OF 11)

```
ECONOMIZE....REDUCE DIMENSION OF S AND VALUE OF [illegible]

********************************************************************************************************

              SCRAMJET WALL GEOMETRY TEST CASE WITH THE BOUNDARY H AND TAW CALCULATED.

********************************************************************************************************
                                   M A T E R I A L   P R O P E R T I E S
   MATERIAL 1      RHO=[illegible] LBM/CU-FT      K=[illegible] BTU/SEC-FT-DEG R      CP=0.2500 BTU/LBM-DEG R

********************************************************************************************************

                                              T A B L E S
 TIME IN SECONDS
   0.0            0.5000E+01      0.1000E+02      0.2000E+02
 ALTITUDE IN FEET
   0.4000E+05     0.4000E+05      0.4000E+05      0.4000E+05
 VELOCITY IN FEET PER SEC.
   0.3000E+04     0.3000E+04      0.3000E+04      0.3000E+04
 ANGLE OF ATTACK IN DEGREES
   0.0            0.0             0.0             0.0

                                              T A B L E S
                          TABLES 2 AND 3 GIVE H AND TAW   FOR BOTTOM SURFACE OF WALL
  2    3                  SCRAMJET WALL INNER SURFACE HT DIST.
0.0         0.0         0.2000E+03  0.0         0.0         0.0         0.0         0.0         0.0         0.0
0.0         0.5550E-02  0.5550E-02  0.0         0.0         0.0         0.0         0.0         0.0         0.0
0.4000E+01  0.5550E-02  0.5550E-02  0.0         0.0         0.0         0.0         0.0         0.0         0.0
0.1020E+02  0.5550E-02  0.5550E-02  0.0         0.0         0.0         0.0         0.0         0.0         0.0
  2    3                TAW   SCRAMJET INNER WALL SURFACE DIST.
0.0         0.0         0.2000E+03  0.0         0.0         0.0         0.0         0.0         0.0         0.0
0.0         0.1500E+04  0.1500E+04  0.0         0.0         0.0         0.0         0.0         0.0         0.0
0.4000E+01  0.1500E+04  0.1500E+04  0.0         0.0         0.0         0.0         0.0         0.0         0.0
0.1020E+02  0.1500E+04  0.1500E+04  0.0         0.0         0.0         0.0         0.0         0.0         0.0
  0    0

********************************************************************************************************
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CONSTANT MATERIAL PROPERTIES

TRAJECTORY TABLES FOR UPPER SCRAMJET WALL BOUNDARY

H & T_{AW} TABLES READ IN FOR SCRAMJET WALL LOWER BOUNDARIES

1827-020B

SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 5 OF 11)

N O D A L   N E T W O R K

NODE ARRANGEMENT – RESEMBLES SCRAMJET WALL GEOMETRY

NODE NUMBERS

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	1.0	7.0	13.0	19.0	25.0	31.0	37.0	43.0	49.0	55.0
2	0.0	8.0	14.0	20.0	26.0	32.0	38.0	44.0	50.0	56.0
3	0.0	0.0	15.0	21.0	27.0	33.0	39.0	45.0	51.0	57.0
4	0.0	0.0	0.0	22.0	28.0	34.0	40.0	46.0	52.0	58.0
5	0.0	0.0	0.0	0.0	29.0	35.0	41.0	47.0	53.0	59.0
6	0.0	0.0	0.0	0.0	0.0	36.0	42.0	48.0	54.0	60.0
ROW / COL	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	61.0	67.0	73.0	79.0	85.0	91.0	97.0	103.0	109.0	115.0
2	62.0	68.0	74.0	80.0	86.0	92.0	98.0	104.0	110.0	116.0
3	63.0	69.0	75.0	81.0	87.0	93.0	99.0	105.0	111.0	117.0
4	64.0	70.0	76.0	82.0	88.0	94.0	100.0	106.0	112.0	0.0
5	65.0	71.0	77.0	83.0	89.0	95.0	101.0	107.0	0.0	0.0
6	66.0	72.0	78.0	84.0	90.0	96.0	102.0	0.0	0.0	0.0
ROW / COL	**21**	**22**								
1	121.0	127.0								
2	122.0	0.0								
3	0.0	0.0								
4	0.0	0.0								
5	0.0	0.0								
6	0.0	0.0								

MATERIAL NUMBER AT EACH NODE

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0
6	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0
ROW / COL	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0
6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0
ROW / COL	**21**	**22**								
1	1.0	1.0								
2	1.0	0.0								
3	0.0	0.0								
4	0.0	0.0								
5	0.0	0.0								
6	0.0	0.0								

ONE MATERIAL THROUGHOUT

1827-021B

SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 6 OF 11)

CAPACITANCE AT EACH NODE

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	0.264E+00	0.105E+01	0.105E+01	0.105E+01	0.105E+01	0.527E+00	0.879E+00	0.879E+00	0.879E+00	0.879E+00
2	0.0	0.105E+01	0.211E+01	0.211E+01	0.211E+01	0.105E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01
3	0.0	0.0	0.105E+01	0.211E+01	0.211E+01	0.105E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01
4	0.0	0.0	0.0	0.105E+01	0.211E+01	0.105E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01
5	0.0	0.0	0.0	0.0	0.105E+01	0.105E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01
6	0.0	0.0	0.0	0.0	0.0	0.264E+00	0.879E+00	0.879E+00	0.879E+00	0.879E+00

ROW / COL	11	12	13	14	15	16	17	18	19	20
1	0.879E+00	0.879E+00	0.879E+00	0.879E+00	0.879E+00	0.879E+00	0.352E+00	0.703E+00	0.703E+00	0.703E+00
2	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.703E+00	0.141E+01	0.141E+01	0.141E+01
3	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.703E+00	0.141E+01	0.141E+01	0.703E+00
4	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.703E+00	0.141E+01	0.703E+00	0.0
5	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.176E+01	0.703E+00	0.703E+00	0.0	0.0
6	0.879E+00	0.879E+00	0.879E+00	0.879E+00	0.879E+00	0.879E+00	0.176E+00	0.0	0.0	0.0

ROW / COL	21	22
1	0.703E+00	0.176E+00
2	0.703E+00	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0

ZERO VALUES, BECAUSE THERE ARE NO NODES AT THESE LOCATIONS

CONDUCTANCE IN X-DIRECTION

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	0.359E-02	0.359E-02	0.359E-02	0.359E-02	0.478E-02	0.239E-02	0.431E-02	0.431E-02	0.431E-02	0.431E-02
2	0.0	0.718E-02	0.718E-02	0.718E-02	0.957E-02	0.108E-01	0.861E-02	0.861E-02	0.861E-02	0.861E-02
3	0.0	0.0	0.718E-02	0.718E-02	0.957E-02	0.108E-01	0.861E-02	0.861E-02	0.861E-02	0.861E-02
4	0.0	0.0	0.0	0.718E-02	0.957E-02	0.108E-01	0.861E-02	0.861E-02	0.861E-02	0.861E-02
5	0.0	0.0	0.0	0.0	0.957E-02	0.108E-01	0.861E-02	0.861E-02	0.861E-02	0.861E-02
6	0.0	0.0	0.0	0.0	0.0	0.538E-02	0.431E-02	0.431E-02	0.431E-02	0.431E-02

ROW / COL	11	12	13	14	15	16	17	18	19	20
1	0.431E-02	0.431E-02	0.431E-02	0.431E-02	0.431E-02	0.215E-02	0.718E-02	0.538E-02	0.538E-02	0.538E-02
2	0.861E-02	0.861E-02	0.861E-02	0.861E-02	0.861E-02	0.123E-01	0.144E-01	0.108E-01	0.108E-01	0.108E-01
3	0.861E-02	0.861E-02	0.861E-02	0.861E-02	0.861E-02	0.123E-01	0.144E-01	0.108E-01	0.108E-01	0.0
4	0.861E-02	0.861E-02	0.861E-02	0.861E-02	0.861E-02	0.123E-01	0.144E-01	0.108E-01	0.0	0.0
5	0.861E-02	0.861E-02	0.861E-02	0.861E-02	0.861E-02	0.123E-01	0.144E-01	0.0	0.0	0.0
6	0.431E-02	0.431E-02	0.431E-02	0.431E-02	0.431E-02	0.615E-02	0.0	0.0	0.0	0.0

ROW / COL	21	22
1	0.718E-02	0.0
2	0.0	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0

ZERO VALUES, BECAUSE THERE ARE NO NODES TO THE RIGHT OF THESE

1827-022B

SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 7 OF 11)

CONDUCTANCE IN Y-DIRECTION

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	0.0	0.258E+00	0.258E+00	0.258E+00	0.258E+00	0.129E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00
2	0.0	0.0	0.258E+00	0.258E+00	0.258E+00	0.129E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00
3	0.0	0.0	0.0	0.258E+00	0.258E+00	0.129E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00
4	0.0	0.0	0.0	0.0	0.258E+00	0.129E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00
5	0.0	0.0	0.0	0.0	0.0	0.172E+00	0.287E+00	0.287E+00	0.287E+00	0.287E+00
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW / COL	11	12	13	14	15	16	17	18	19	20
1	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.861E-01	0.172E+00	0.172E+00	0.172E+00
2	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.961E-01	0.172E+00	0.172E+00	0.172E+00
3	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.861E-01	0.172E+00	0.172E+00	0.0
4	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.215E+00	0.861E-01	0.172E+00	0.0	0.0
5	0.287E+00	0.287E+00	0.287E+00	0.287E+00	0.287E+00	0.287E+00	0.115E+00	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW / COL	21	22
1	0.172E+00	0.0
2	0.0	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0

ZERO VALUES BECAUSE THERE ARE NO NODES BELOW THESE

INITIAL TEMPERATURE DISTRIBUTION DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
2	0.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
3	0.0	0.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
4	0.0	0.0	0.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
5	0.0	0.0	0.0	0.0	500.0	500.0	500.0	500.0	500.0	500.0
6	0.0	0.0	0.0	0.0	0.0	500.0	500.0	500.0	500.0	500.0

ROW / COL	11	12	13	14	15	16	17	18	19	20
1	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
2	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
3	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
4	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	0.0
5	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	0.0	0.0
6	500.0	500.0	500.0	500.0	500.0	500.0	500.0	0.0	0.0	0.0

ROW / COL	21	22
1	500.0	500.0
2	500.0	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0

****

1827-023B

SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 8 OF 11)

****

***** T I M E = 0.1200E+03 S E C O N D S *****

MACH= [illegible] ALTITUDE= 40000.0 VELOCITY= 3000.00 ANGLE OF ATTACK= 0.0

AVERAGE HEAT TRANSFER COEFFICIENTS BTU/SEC-FT**2-DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	0.117E-01	0.116E-01	0.114E-01	0.110E-01	0.107E-01	0.103E-01	0.100E-01	0.971E-02	0.942E-02	[illegible]
2	0.0	0.555E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.555E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.555E-02	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.555E-02	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02

ROW / COL	11	12	13	14	15	16	17	18	19	20
1	[illegible]	[illegible]	0.844E-02	0.824E-02	0.805E-02	0.787E-02	0.771E-02	0.756E-02	0.742E-02	0.729E-02
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.555E-02
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.555E-02	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.555E-02	0.0	0.0
6	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.555E-02	0.0	0.0	0.0

ROW / COL	21	22
1	0.717E-02	0.705E-02
2	0.555E-02	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0

AVERAGE HEAT TRANSFER COUPLINGS BTU/SEC-DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	[illegible]	[illegible]	0.602E-02	[illegible]	[illegible]	[illegible]	0.501E-02	0.486E-02	0.471E-02	0.457E-02
2	0.0	[illegible]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	[illegible]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.330E-02	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.330E-02	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	[illegible]	0.277E-02	0.277E-02	0.277E-02	0.277E-02

ROW / COL	11	12	13	14	15	16	17	18	19	20
1	[illegible]	[illegible]	0.422E-02	0.412E-02	0.402E-02	[illegible]	0.154E-02	0.302E-02	0.297E-02	0.292E-02
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.229E-02
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.229E-02	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.229E-02	0.0	0.0
6	[illegible]	0.277E-02	0.277E-02	0.277E-02	0.277E-02	0.277E-02	0.114E-02	0.0	0.0	0.0

ROW / COL	21	22
1	[illegible]	[illegible]
2	[illegible]	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0

1827-024B

SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 9 OF 11)

AVERAGE ADIABATIC WALL TEMPERATURE DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0
2	0.0	1500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	1500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	1500.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	1500.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	1500.0	1500.0	1500.0	1500.0	1500.0

ROW / COL	11	12	13	14	15	16	17	18	19	20
1	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0	1039.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1500.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1500.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1500.0	0.0	0.0
6	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	0.0	0.0	0.0

ROW / COL	21	22
1	1039.0	1039.0
2	1500.0	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0

TEMPERATURES AT THIS TIME DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	883.5	757.6	671.6	627.8	600.7	584.7	576.6	578.5	578.0	572.2
2	0.0	757.4	666.3	620.6	592.5	576.2	568.1	570.2	570.0	564.5
3	0.0	0.0	670.1	620.5	589.8	572.4	564.1	566.4	566.5	561.0
4	0.0	0.0	0.0	627.2	592.5	573.4	564.7	567.1	567.3	562.0
5	0.0	0.0	0.0	0.0	600.7	579.0	569.8	572.3	572.5	567.3
6	0.0	0.0	0.0	0.0	0.0	586.7	577.0	579.5	579.8	574.6

ROW / COL	11	12	13	14	15	16	17	18	19	20
1	570.3	573.4	572.6	567.3	567.[illegible]	573.2	577.8	583.8	604.0	650.7
2	562.8	566.1	[illegible]	560.4	563.4	566.7	571.6	578.2	599.3	647.5
3	559.5	563.1	562.6	557.6	557.6	564.4	569.9	577.4	600.3	651.2
4	560.6	564.3	563.9	559.0	559.3	566.1	572.3	581.3	607.0	0.0
5	566.0	565.8	569.5	564.6	565.0	571.9	579.0	589.8	0.0	0.0
6	573.3	577.1	576.9	572.0	572.4	579.4	586.8	0.0	0.0	0.0

ROW / COL	21	22
1	729.6	759.7
2	730.1	0.0
	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0

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SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 10 OF 11)

STEADY-STATE TEMPERATURES FOR THE BOUNDARY CONDITIONS AT THIS TIME DEG.R

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	1167.8	1175.2	1185.5	1190.5	1193.9	1196.1	1198.2	1200.8	1203.6	1206.4
2	0.0	1175.6	1189.5	1194.4	1197.7	1199.9	1201.9	1204.5	1207.2	1209.9
3	0.0	0.0	1194.0	1198.4	1201.5	1203.7	1205.6	1208.1	1210.8	1213.5
4	0.0	0.0	0.0	1202.3	1205.4	1207.5	1209.3	1211.6	1214.4	1217.1
5	0.0	0.0	0.0	0.0	1209.3	1211.3	1213.0	1215.4	1218.0	1220.6
6	0.0	0.0	0.0	0.0	0.0	1214.1	1215.7	1218.1	1220.7	1223.3
ROW / COL	11	12	13	14	15	16	17	18	19	20
1	1209.2	1211.9	1214.5	1217.1	1219.5	1221.7	1223.2	1224.4	1225.3	1224.5
2	1212.7	1215.4	1218.0	1220.5	1222.8	1225.1	1226.5	1227.7	1228.5	1227.8
3	1216.2	1218.8	1221.4	1223.9	1226.2	1228.4	1229.9	1231.0	1231.9	1231.4
4	1219.7	1222.3	1224.9	1227.3	1229.6	1231.8	1233.2	1234.3	1235.3	0.0
5	[illegible]	[illegible]	[illegible]	1230.7	1233.0	1235.2	1236.6	1237.7	0.0	0.0
6	1229.9	1228.5	[illegible]	1233.3	1235.5	1237.7	1239.1	0.0	0.0	0.0
ROW / COL	21	22								
1	[illegible]	[illegible]								
2	[illegible]	0.0								
3	0.0	0.0								
4	0.0	0.0								
5	0.0	0.0								
6	0.0	0.0								

INTEGRATED HEAT INPUT AT EACH NODE BTU

ROW / COL	1	2	3	4	5	6	7	8	9	10
1	65.7	201.7	300.6	327.0	337.4	169.2	276.0	268.4	260.6	256.2
2	0.0	284.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	336.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	353.6	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	364.3	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	185.0	307.3	306.5	306.4	308.2
ROW / COL	11	12	13	14	15	16	17	18	19	20
1	250.2	241.9	236.2	233.2	227.9	220.0	85.4	165.2	155.0	135.9
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	233.1
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	245.2	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	249.9	0.0	0.0
6	308.6	307.3	307.4	309.0	308.9	336.6	125.4	0.0	0.0	0.0
ROW / COL	21	22								
1	106.5	47.3								
2	211.4	0.0								
3	0.0	0.0								
4	0.0	0.0								
5	0.0	0.0								
6	0.0	0.0								

***** T I M E = 0.1400E+03 S E C O N D S *****

AMACH= 3.059 ALTITUDE= 40000.0 VELOCITY= 3000.00 ANGLE OF ATTACK=

1827-026B AVERAGE HEAT TRANSFER COEFFICIENTS

SHEET 4.3 INPUT/OUTPUT DATA FOR SCRAMJET ENGINE SIDE-WALL PROBLEM (SHEET 11 OF 11)

Section 5

SPECIAL OUTPUT FILES

5.1 DISCUSSION

A option has been added to CAVE that will create a special file containing heat transfer coefficients, average adiabatic wall temperatures, and node temperature for pre-selected nodes at each print time. This file can be useful for making quick comparisons of these parameters in areas of the geometry that are critical. This file also can be used for generation of time-history plots of these parameters. The user can select this option for any of the available geometries.

The user must assign a logical unit number for the special output file. The variable NODOUT, defined at line 1030 in Subroutine OVLY21, must be set equal to this logical unit number, and provision must be made in the user's job control language (JCL) to allocate a disk file, tape unit, etc. for this purpose.

5.2 INPUT DATA FORMAT

The inputs that specify the nodes for which data will be written into the special file follow the Initial Temperature Cards. For example:

Initial Temperature Cards

- KODE, I, T(I), II, JJ
- ...
- ...
- 11100 (signifies end of temperature cards).

Special Output File Card(s)

- NPLOTS, ITCODE (2I4)
- NODNUM(1), NODNUM(2), ... NODNUM (NPLOTS)
  (Omit if NPLOTS = 0) (20I4)

  NPLOTS = Number of nodes whose data will be written into special output file. If NPLOTS = 0, option is not being used.

ITCODE	=	1 If node temperatures in special file are to be in R
ITCODE	=	2 If node temperatures in special file are to be in K
NODNUM(I)	=	Node number of temperature to be stored I = 1, 2, 3 ... NPLOTS.

Note: If the special output file option is not used, NPLOTS cannot be omitted and must be read in as zero.

5.3 SAMPLE INPUT & OUTPUT DATA

The following pages show sample input data to exercise this option and the resultant output data.

```
TEST CASE FOR SOLID BLUNT NOSED CONE
0.0        0.0
   1
        0      169.    0.04306     0.208
        5       10.
     0.05       0.1        0.2        0.2        0.2        0.2        0.2        0.2
     0.2        0.2
     0.05       0.1        0.1        0.1        0.05
      0.0
   0    1      500.    75     1  <-- INITIAL TEMPERATURE CARDS
11100  <-- SIGNIFIES END OF TEMPERATURE CARDS
  6   1  <-- NPLOTS, ITCODE
  1   3  11  24  29  47  <-- NODE NUMBERS FOR SPECIAL OUTPUT FILE
      0.0       -1.0        0
0206                 BLUNT NOSED CONE HT DIST.                          00
        0.0    155.                                                     01
0.0    .00555 .00555                                                    02
0.3    .00555 .00555                                                    03
.75    .00555 .00555                                                    04
1.50   .00555 .00555                                                    05
2.25   .00555 .00555                                                    06
2.7    .00555 .00555                                                    07
0206             BLUNT NOSED CONE TAW DIST.                             00
        0.0    155.                                                     01
0.0    1500.  1500.                                                     02
0.3    1500.  1500.                                                     03
.75    1500.  1500.                                                     04
1.50   1500.  1500.                                                     05
2.25   1500.  1500.                                                     06
2.7    1500.  1500.                                                     07
```

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SHEET 5.3 SAMPLE INPUT DATA FOR SPECIAL OUTPUT FILE (SHEET 1 OF 2)

NODE NUMBERS

TIME

HEAT TRANSFER COEFFICIENT

TADIABATIC WALL

NODE TEMPERATURE AT THIS TIME

```
   1
0.20000E+02 0.55500E-02 0.15000E+04 0.52914E+03
0.50000E+02 0.55500E-02 0.15000E+04 0.56230E+03
0.10000E+03 0.55500E-02 0.15000E+04 0.61251E+03
0.15000E+03 0.55500E-02 0.15000E+04 0.65694E+03
   3
0.20000E+02 0.0         0.0         0.51899E+03
0.50000E+02 0.0         0.0         0.55235E+03
0.10000E+03 0.0         0.0         0.60274E+03
0.15000E+03 0.0         0.0         0.64738E+03
  11
0.20000E+02 0.55500E-02 0.15000E+04 0.52662E+03
0.50000E+02 0.55500E-02 0.15000E+04 0.55966E+03
0.10000E+03 0.55500E-02 0.15000E+04 0.60947E+03
0.15000E+03 0.55500E-02 0.15000E+04 0.65362E+03
  24
0.20000E+02 0.0         0.0         0.51606E+03
0.50000E+02 0.0         0.0         0.54867E+03
0.10000E+03 0.0         0.0         0.59770E+03
0.15000E+03 0.0         0.0         0.64137E+03
  29
0.20000E+02 0.0         0.0         0.51469E+03
0.50000E+02 0.0         0.0         0.54705E+03
0.10000E+03 0.0         0.0         0.59567E+03
0.15000E+03 0.0         0.0         0.63907E+03
  47
0.20000E+02 0.0         0.0         0.51974E+03
0.50000E+02 0.0         0.0         0.54469E+03
0.10000E+03 0.0         0.0         0.58426E+03
0.15000E+03 0.0         0.0         0.62134E+03
```

THESE VALUES ARE ZERO BECAUSE THE NODES ARE NOT SURFACE NODES

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SHEET 5.3 SAMPLE INPUT DATA FOR SPECIAL OUTPUT FILE (SHEET 2 OF 2)

Section 6

CONVECTIVE HEAT TRANSFER COEFFICIENTS FOR LEADING-EDGE GEOMETRY

6.1 DISCUSSION

The CAVE code has been expanded to provide the user the following options for computing the heat transfer coefficients on the leading-edge geometry:

- Option 1 - Entire flow over the leading-edge is assumed to be laminar
- Option 2 - Entire flow over the leading-edge is assumed to be turbulent
- Option 3 - Flow over the leading-edge is laminar up to a specified (i.e., input value) location where the flow transitions is turbulent for the balance of the leading-edge.

Options 1 and 2 were available in the original CAVE code. No change was made to these options. Option 3 is new and requires that the user specify the locations of the laminar to turbulent transitions on both the upper and lower leading-edge surfaces. Subsection 6.2 gives the required input data for the three options.

For option 3, subroutine LEES2 calculates the turbulent heat transfer coefficient downstream of the transition point with suitable modification to reflect the upstream laminar flow influence on the boundary layer thickness. The development of the modification is now presented.

The turbulent boundary layer thermal displacement thickness can be defined as:

$$\delta^*_{th} = C_T S^{4/5}$$

where C_T is a coefficient encompassing fluid properties and flow conditions, and S represents the distance measured along the surface from X = 0 to the point at which flow transition occurs.

For laminar boundary layers, δ^*_{th} is proportional to the total heat transfer.

i.e., $$\delta^*_{th,\,laminar} = \frac{\dot{Q}_{laminar}}{\rho_\infty V_\infty (H_\infty - H_W)}$$

where H_∞ and H_W are the freestream and wall enthalpies.

Because $\dot{Q}_{turb} = \dot{Q}_{lam} \left(\frac{h_{o,\,turb}}{h_{o,\,lam}}\right)$ (h_o = stagnation point heat transfer coefficient)

and because at the point where transition occurs the following relationship must be satisfied:

$$\delta^*_{th,\,turb} = \delta^*_{th,\,lam} \; ;$$

it follows that

$$\delta^*_{th\,,\,turb} = C_T S_{eff}^{4/5} = \frac{\dot{Q}_{lam}}{\rho_\infty V_\infty \, (H_\infty - H_w)} = \frac{\dot{Q}_{turb} \left(\frac{h_{o,\,lam}}{h_{o,\,turb}}\right)}{\rho_\infty V_\infty \, (H_\infty - H_w)}$$

where S_{eff} is the effective position of the transition point.

However,

$$C_T S_{transition}^{4/5} = \frac{\dot{Q}_{turb}}{\rho_\infty V_\infty \, (H_\infty - H_w)}$$

therefore: $C_T S_{eff}^{4/5} = C_T S_{trans}^{4/5} \left(\frac{h_{o,\,lam}}{h_{o,\,turb}}\right)$

or $\quad S_{eff} = S_{trans}\left(\frac{h_{o,\,lam}}{h_{o,\,turb}}\right)^{5/4}$

This equation gives the relationship between the effective and the actual positions of the laminar to turbulent transition.

Within LEES2 the integral $\int_0^S P\,U\,dS$ (used to compute the heat transfer coefficients) has been modified to account for transition. The following equation is employed for locations at or beyond the transition point:

$$\int_0^S P\,U\,dS = \left(\frac{h_{o,\,lam}}{h_{o,\,turb}}\right)^{5/4} \int_0^{S_{trans}} P\,U\,dS \; + \int_{S_{trans}}^{S} P\,U\,dS$$

6.2 INPUT DATA FORMAT FOR LEADING-EDGE GEOMETRY WITH LAMINAR AND/OR TURBULENT HEATING

The input data for the leading-edge geometry is unaltered with one exception. For the laminar to turbulent transition case, two additional input values are required:

STRANU and STRANL which specify the transition locations. The so-called Wing Angles card, part of the input data package for the leading-edge geometry, now includes these two new parameters. The format is as follows:

Wing Angles Card

- SWEEPA, DIHEDA, CODEX, HMODI, TURBL, STRANU, STRANL (7E10.0)

SWEEPA	=	wing sweep angle, in degrees
DIHEDA	=	wing dihedral angle, in degrees
CODEX	=	0. for convective coefficient and adiabatic wall temperature computed by CAVE; = -1. for tabular input of coefficients and temperatures
HMODI	=	nonzero value indicates that two tables will be read at the end and used to multiply the convective coefficient
TURBL	=	less than zero, entire flow is assumed to be laminar
	=	0. entire flow is assumed to be turbulent
	=	greater than zero, a location has been specified on the upper and lower leading-edge surface where flow transitions from laminar to turbulent
STRANU	=	X location at which flow transitions on the upper surface (required only for TURBL >0)
STRANL	=	X location at which flow transitions on the lower surface (required only for TURBL >0).

Section 7

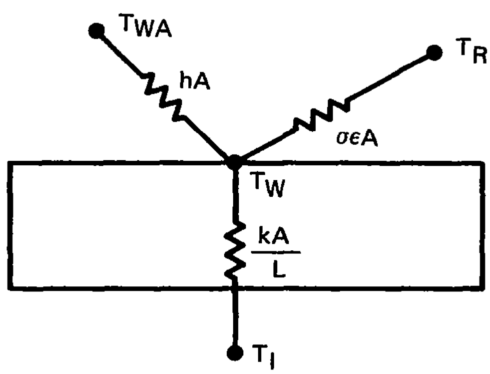
MODIFICATION TO RADIATION CALCULATION PROCEDURE

Heat transfer problems involving radiation are non-linear and therefore not exactly tractable with the CAVE eigenvalue-eigenvector solution technique. The linearization procedure used in the original CAVE code is the common one of modifying the convection coupling to account for the radiation (see Appendix C of Reference 1). The temperatures of the surface nodes at the beginning of the time subinterval (end of previous time subinterval) established the radiation modifiers. Using temperatures at the beginning of the time subinterval is quite satisfactory for problems in which radiation plays a minor role or where the surface temperatures are varying slowly from one time subinterval to the next (e.g., "small" time subintervals).

The code has undergone modifications that permit larger time steps to be utilized in problems where radiation heat transfer is a significant factor. The modifications are such as to provide estimates of the surface temperatures at the end of the time subinterval which are then used with the temperatures at the beginning of the time subinterval to establish modified convection couplings for the time subinterval (i.e., the code now uses a mean temperature for the subinterval rather than the temperature at the start of the subinterval).

The following discussion outlines the new procedure that has been incorporated into the code.

Consider a node diagram for a surface node of a body:



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where

hA	=	convection coupling, Btu/sec-R
$\sigma\epsilon A$	=	radiation coupling, Btu/sec-R^4
$\frac{kA}{L}$	=	conduction coupling, Btu/sec-R
T_{AW}	=	adiabatic wall temperature of fluid (more properly referred to as recovery temperature of fluid, R
T_R	=	background radiation temperature (usually taken as $0\,^\circ R$), $^\circ R$
T_W	=	temperature of surface node, R
T_I	=	temperature of interior node, R

The heat transfer into the surface due to convection and radiation is

$$\dot{Q}_{in} = h\,A\,(T_{AW} - T_W) + \sigma\epsilon A\,(T_R^4 - T_W^4) \qquad \text{(Eq. 2)}$$

This may be rewritten as:

$$\dot{Q}_{in} = (h + h_R)\,A\,(T_{AW} - T_W) \qquad \text{(Eq. 3)}$$

where

$$h_R = \frac{\sigma\epsilon\,(T_R^4 - T_W^4)}{(T_{AW} - T_W)} \qquad \text{(Eq. 4)}$$

Eq. (3) can be rewritten into a form suitable for CAVE:

$$\dot{Q}_{in} = h_{eff}\,A\,(T_{AW} - T_W) \qquad \text{(Eq. 5)}$$

where

$$h_{eff} = h + h_R \qquad \text{(Eq. 6)}$$

In the original version of CAVE, T_W was the temperature of the surface at time t, the start of the time interval. In the new version, T_W is the mean of the actual temperature at time t and the estimated temperature at $t + \Delta t$. This estimated temperature is obtained using the h_R values based on the T_W values for time t. Fundamentally, it is a five step process:

1. Calculate h_R based on $T_W(t)$.
2. Calculate T_W $(t+ \Delta t)$ using eigenvalue-eigenvector procedure with h_R from step 1.

3. Calculate mean of T_W (t) and T_W (t + Δt).

4. Recalculate h_R using mean value of T_W from step 3.

5. Recalculate temperature distribution in body using h_R from step 4.

It is noted that h_R is typically negative (see Eq. (4) with $T_W > T_R$) and therefore for conditions with the radiation coupling essentially equal to the convection coupling, h_{eff} approaches zero. If h_{eff} approaches zero over the entire geometry, ill-conditioned matrices may result and the cumulative effect of arithmetic roundoff may preclude convergence of the eigenvector-eigenvalue iteration procedure within subroutine IJEN. A statement to the effect that convergence was not achieved will be printed by CAVE in such situations. The temperatures printed may however be fairly accurate in spite of the lack of convergence. This may be attributed to the eigenvector values being reasonable although not within tolerance and furthermore not being of great significance since the body is not changing very much in temperature due to the very small coupling between it and its environment. Double precision arithmetic would help to alleviate this "ill-conditioned" difficulty.

Appendix

FLOW CHARTS

This appendix presents flow charts for the new subroutines and subroutines that have undergone more than trivial modification.

All CAVE subroutines that have undergone any modification whatsoever have been given slight name changes to avoid any possiblity of the wrong subroutine being used.

TABLE A-1 SUBROUTINES USED IN CAVE (SHEET 1 OF 2)

Name	Called By	Main Purpose
SIZE3	CAVE (main prog)	Computes storage locations needed. Compares to number requested
OVLY10	SIZE3	Sets up arrays for PCP5
PCP5	OVLY10	Reads & writes property data, controls geometry
SLAB2	PCP5	Computes volumes & conduction shape factors for slab & cooled panel geometries
X24C	PCPS	Computes volumes & conduction shape factors for basic X24C geometries
GEN2	PCP5	Reads & writes volumes & conduction shape factors for general geometries
MATOUT	PCP5	Writes material properties
XTABS1	GEN2	Reads tabular values of hA & T_{AW} for general geometry problems
OVLY21	SIZE3	Reads initial temperature distribution & flight trajectory. Controls problem solution, steps time, computes average convection couplings for each step. Writes solution each time step
LINFIT	OVLY21	Finds value from a table by linear interpolation
ATTAC3	OVLY21	Finds node number closest to stagnation point & renumbers nodes as required by LEES2
LEES2	ATTAC3	Computes ratios h/h & T_{AW} variation around leading edge problems
NURED1	OVLY21	Reads tabular values of hA & T_{AW} as functions of distance & time
DINTK	OVLY21	Finds value from a table using double interpolation
PROP	OVLY21	Computes conduction douplings & mass specific heat product for each element given conduction shape factors & volumes
PROUT2	OVLY21	Writes node numbers, conductances, capacitances & initial temperatures
XINTP1	OVLY21	Finds values of several dependent variables from a table by linear interpolation on a single independent variable
FLATH	OVLY21	Finds h & T_{AW} for flow over a flat plate
ATMOS	OVLY21	Finds atmospheric pressure, temperature & density for given altitude
POLRT	FLATH	Computes the roots of a polynominal
TRANS	FLATH	Determines whether flow over flat plate will be considered laminar or turbulent
DESDA2	OVLY21	Calls eigenvalue & matrix routines. Calculates temperatures

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TABLE A-1 SUBROUTINES USED IN CAVE (SHEET 2 OF 2)

Name	Called By	Main Purpose
IJEN2	DESDA2	Obtaines dominant eigenvectors & eigenvalues of a given matrix (using Jennings method of simultaneous vector iteration)
EIGVC	DESDA2	Prepares approximate guesses for the eigenvectors to start the Jennings algorithm iteration for the time step
BFACS	IJEN2	Factorizes a banded positive-definite matrix
BSOLS	DESDA2, IJEN2	Using the factors of a given banded positive-definite A as generated by BFACS solves for X in the system AX = Y
ORNML	IJEN2, DESDA2	Carries out the standard Gram-Schmidt orthonormalization of a group of vectors
HETRA1	DESDA2	Sets up coefficient matrix (of conductances) in compact form
RVORDR	IJEN2	Reorders estimated eigenvalues according to magnitude
AORDER	IJEN2, RVORDER	Sets up permutation indices needed for ordering the eigenvalues
DISPL2	(Various)	Prints information, mainly debug special output, in array form
PART	DESDA2, PCP5	Prints debug output information & intermediate timing of calculation
DATE	PART	Determines data of run
SWITCH	DISPL2	Converts columns of a matrix to rows of visa versa
SCAPR2	(Various)	Computes scalar product of two vectors
WALL2D	SIZE3	Computes volumes & conduction shape factors for Scramjet wall geometry
BLUNT2	PCP5	Computes volumes & conduction shape factors for solid & hollow (cooled) blunt nosed cone geometries
CONSET	OVLY21	Sets up input for LEES2 for analytical solution of blunt nosed cones based on a flight trajectory table
CHECKD	(Various)	Checks completion codes returned from Subroutine DINTK
CHECKN	(Various)	Checks completion codes returned from Subroutine NURED
ROT	POUT	Prints headings for nodal array data for scramjet wall geometry
POUT	WALL2D	Prints out nodal array data for scramjet wall geometry in a format which resembles the geometric shape

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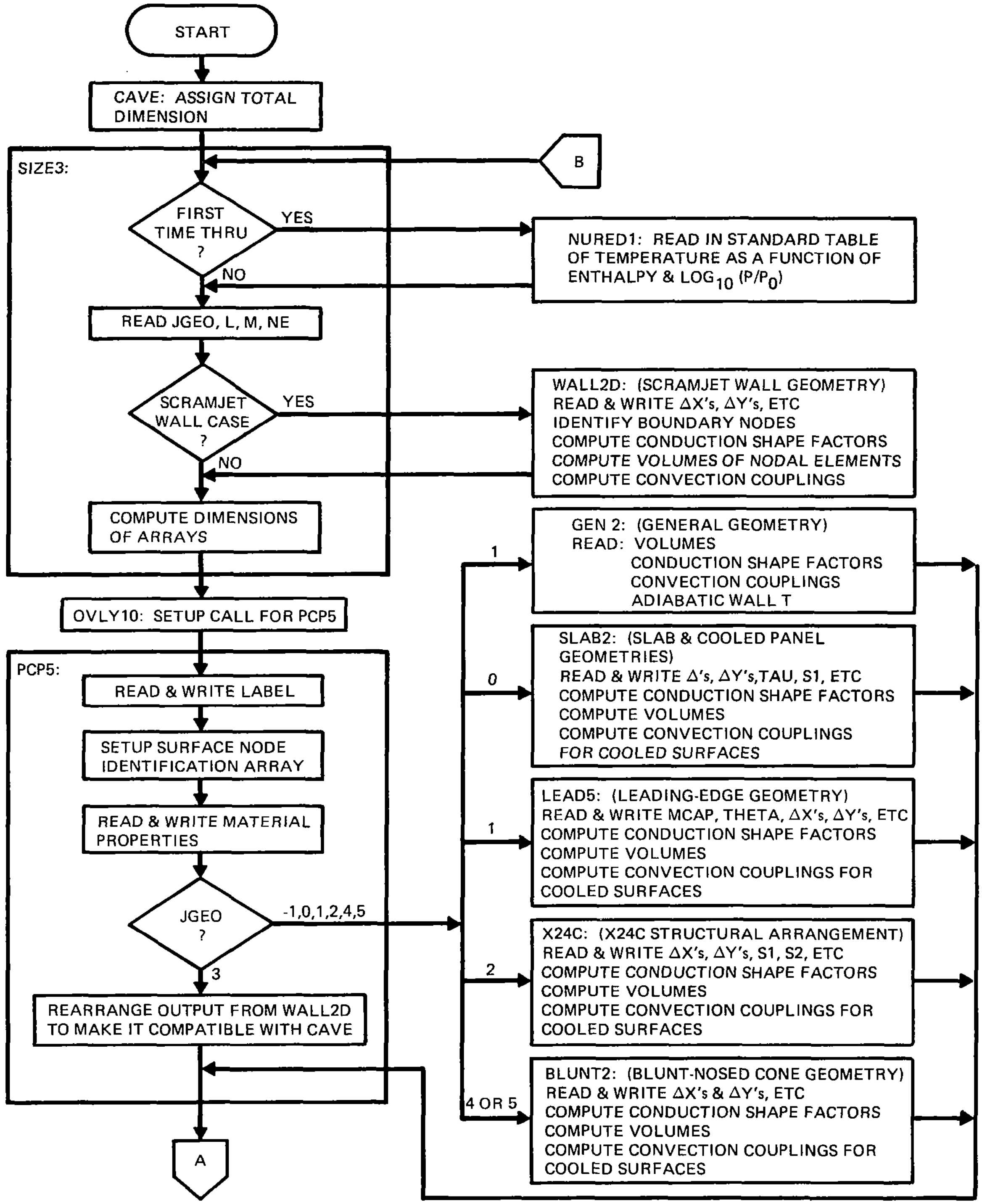


1827-033B

FIG. A-1 ORGANIZATION OF CAVE IN TERMS OF THE MORE IMPORTANT SUBROUTINE CALLS (SHEET 1 OF 2)

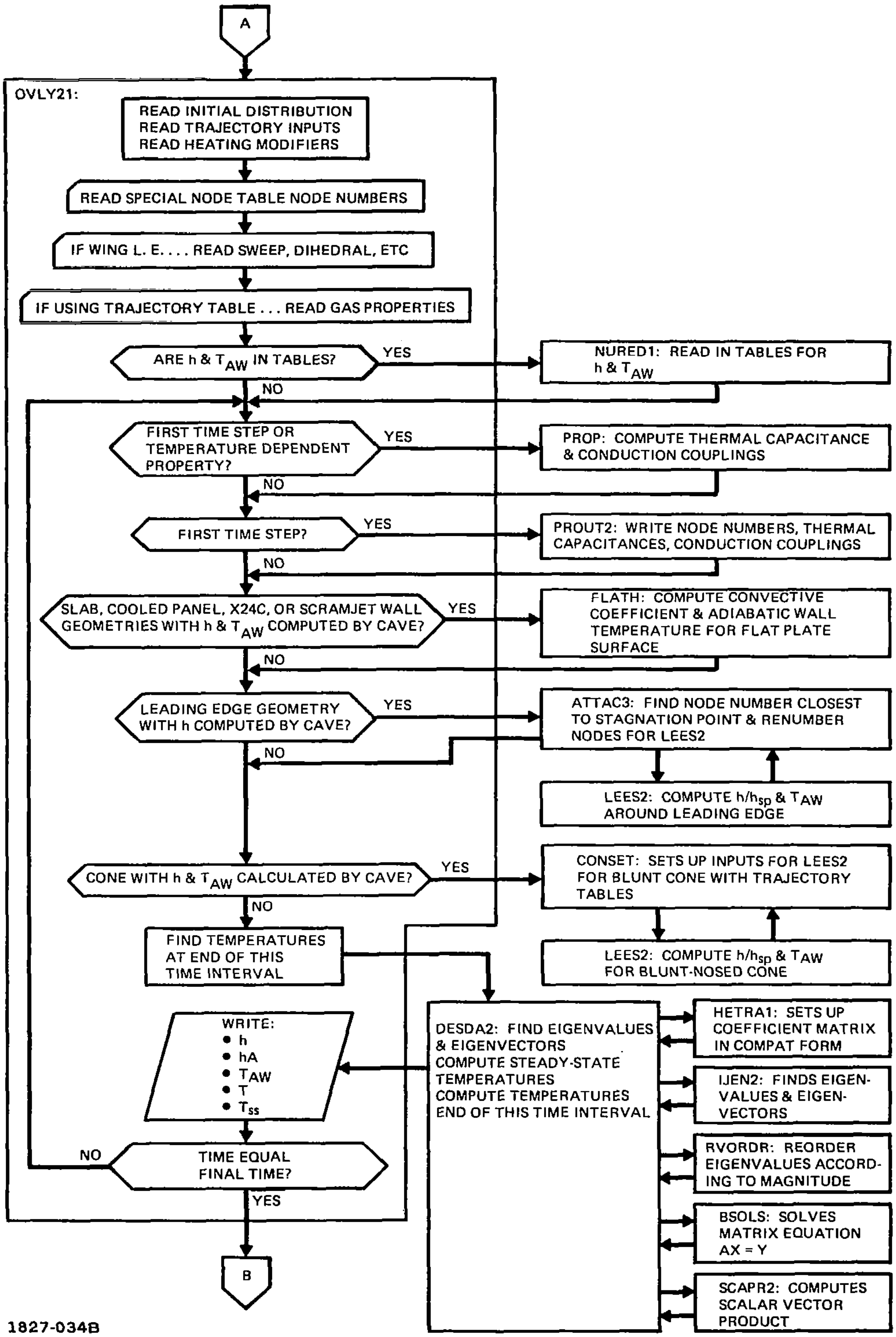
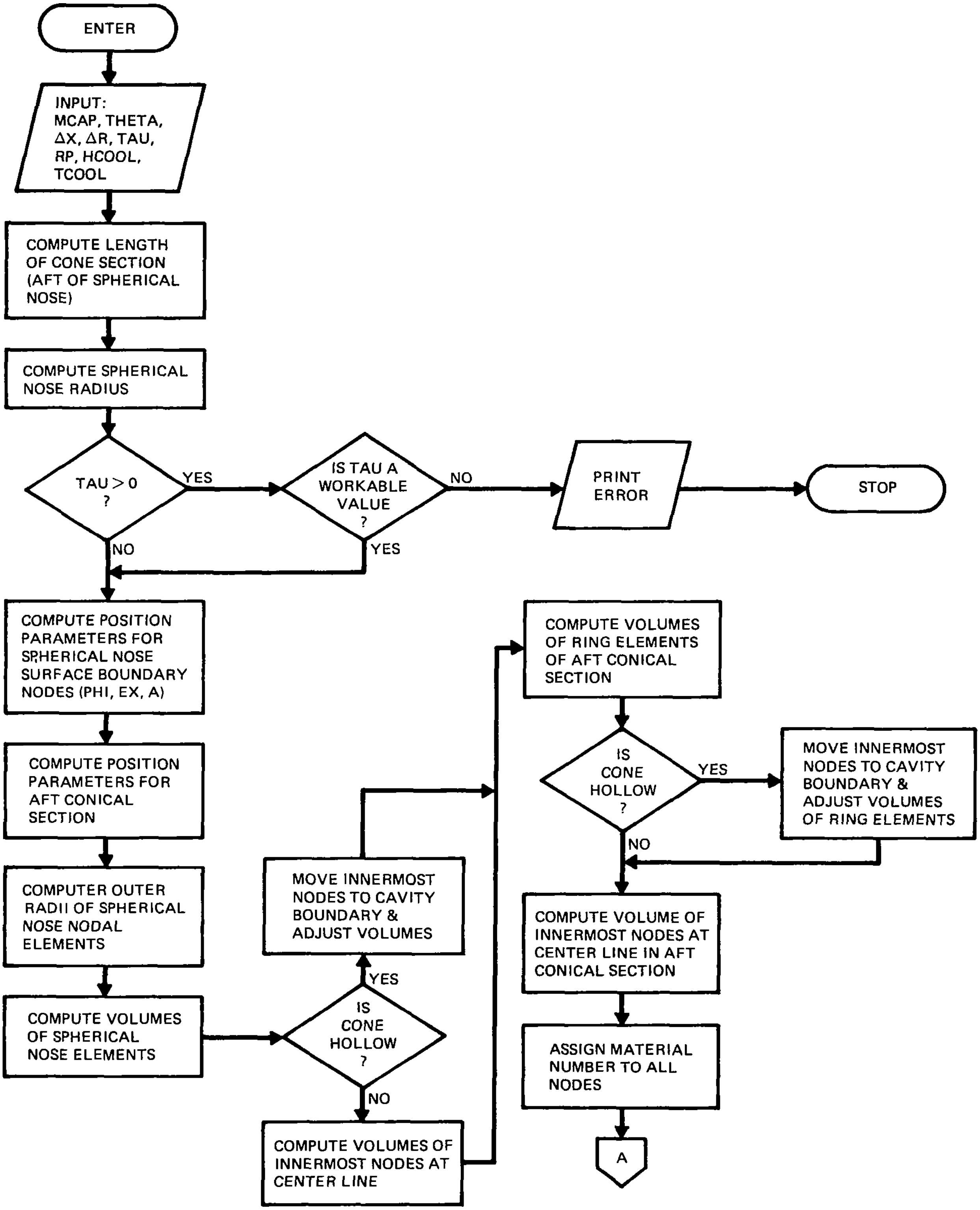
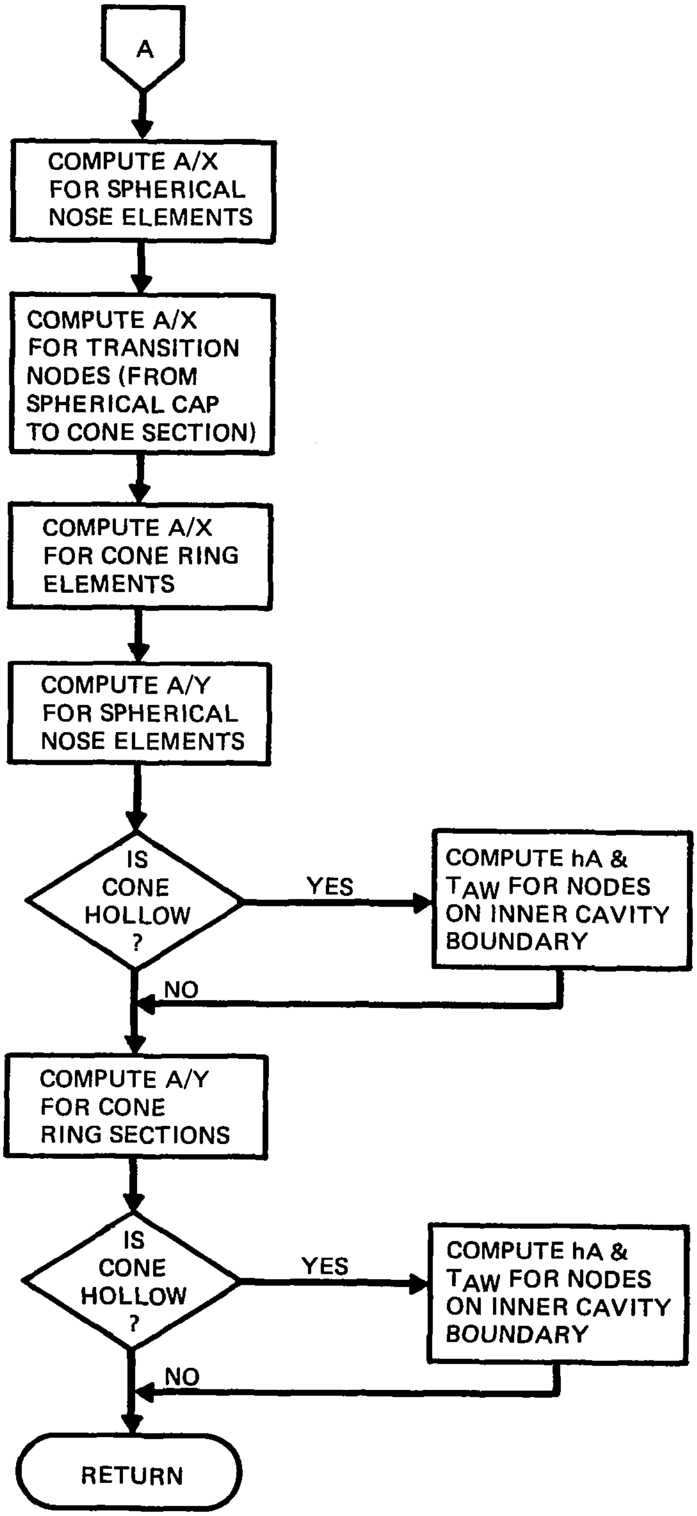


FIG. A-1 ORGANIZATION OF CAVE IN TERMS OF THE MORE IMPORTANT SUBROUTINE CALLS (SHEET 2 OF 2)



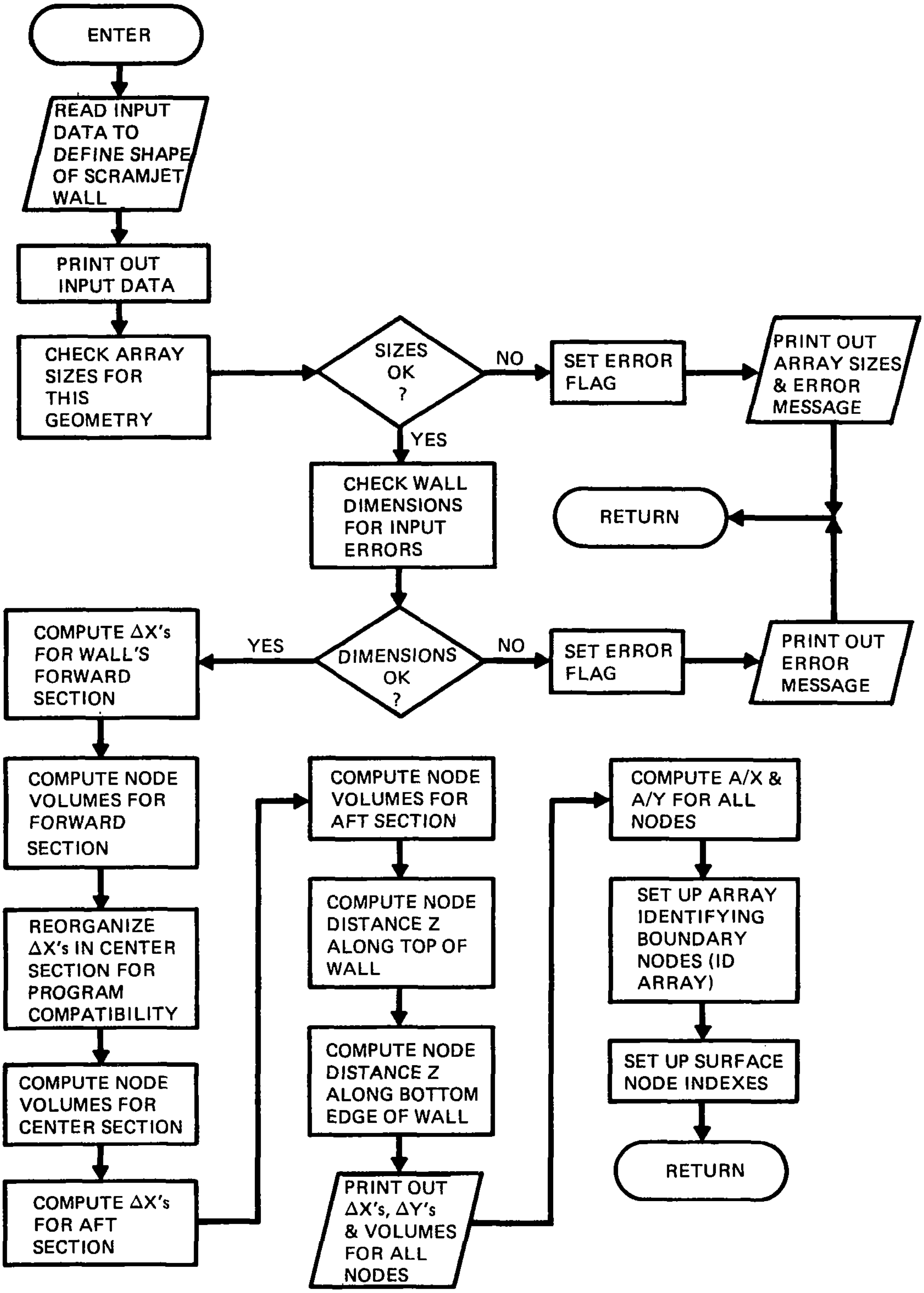
1827-035B

FIG. A-2 SUBROUTINE BLUNT2 FLOW CHART (SHEET 1 OF 2)



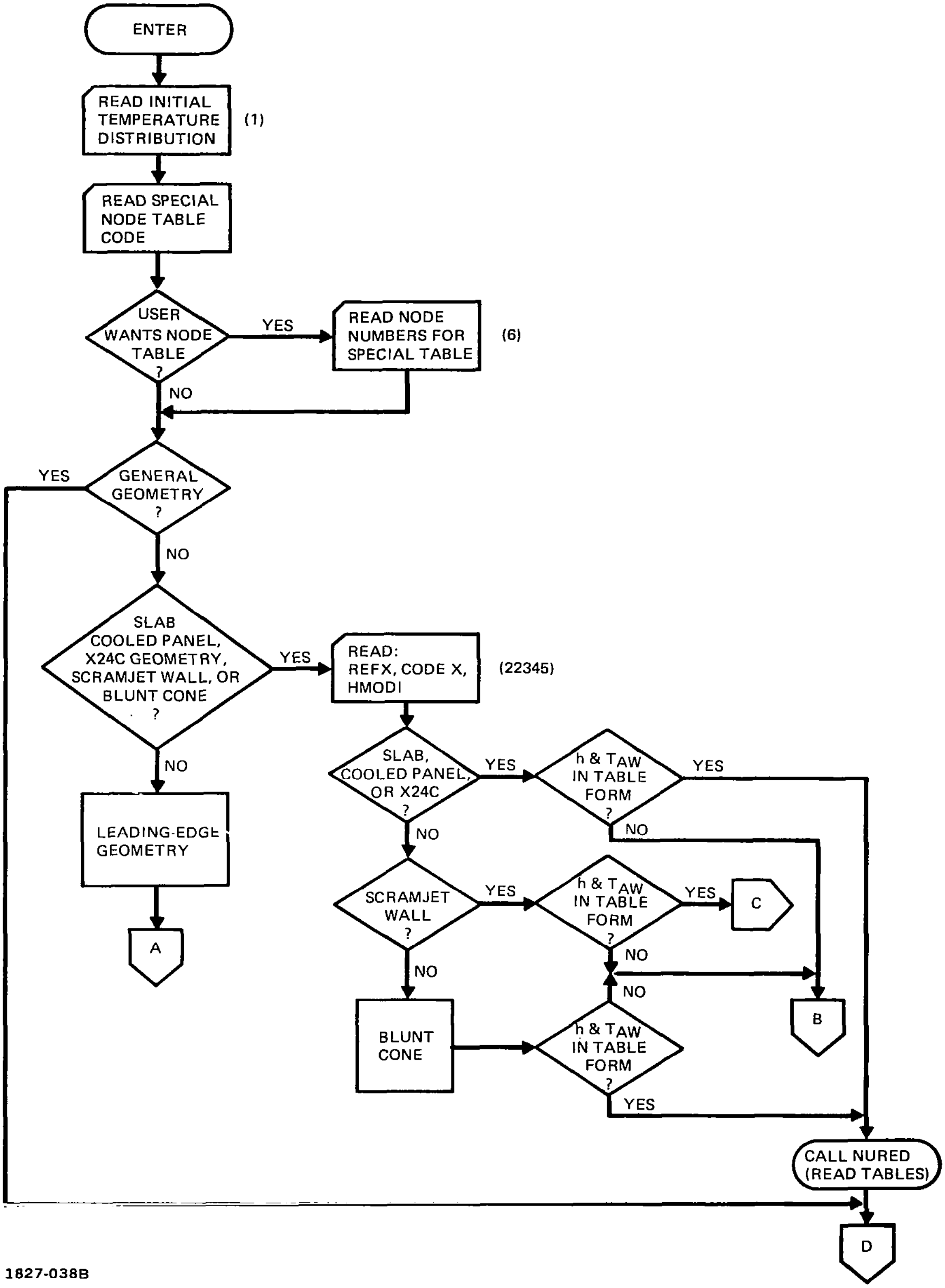
1827-036B

FIG. A-2 SUBROUTINE BLUNT2 FLOW CHART (SHEET 2 OF 2)



1827-037B

FIG. A-3 SUBROUTINE WALL2D FLOW CHART



1827-038B

FIG. A-4 SUBROUTINE OVLY21 FLOW CHART (SHEET 1 OF 6)

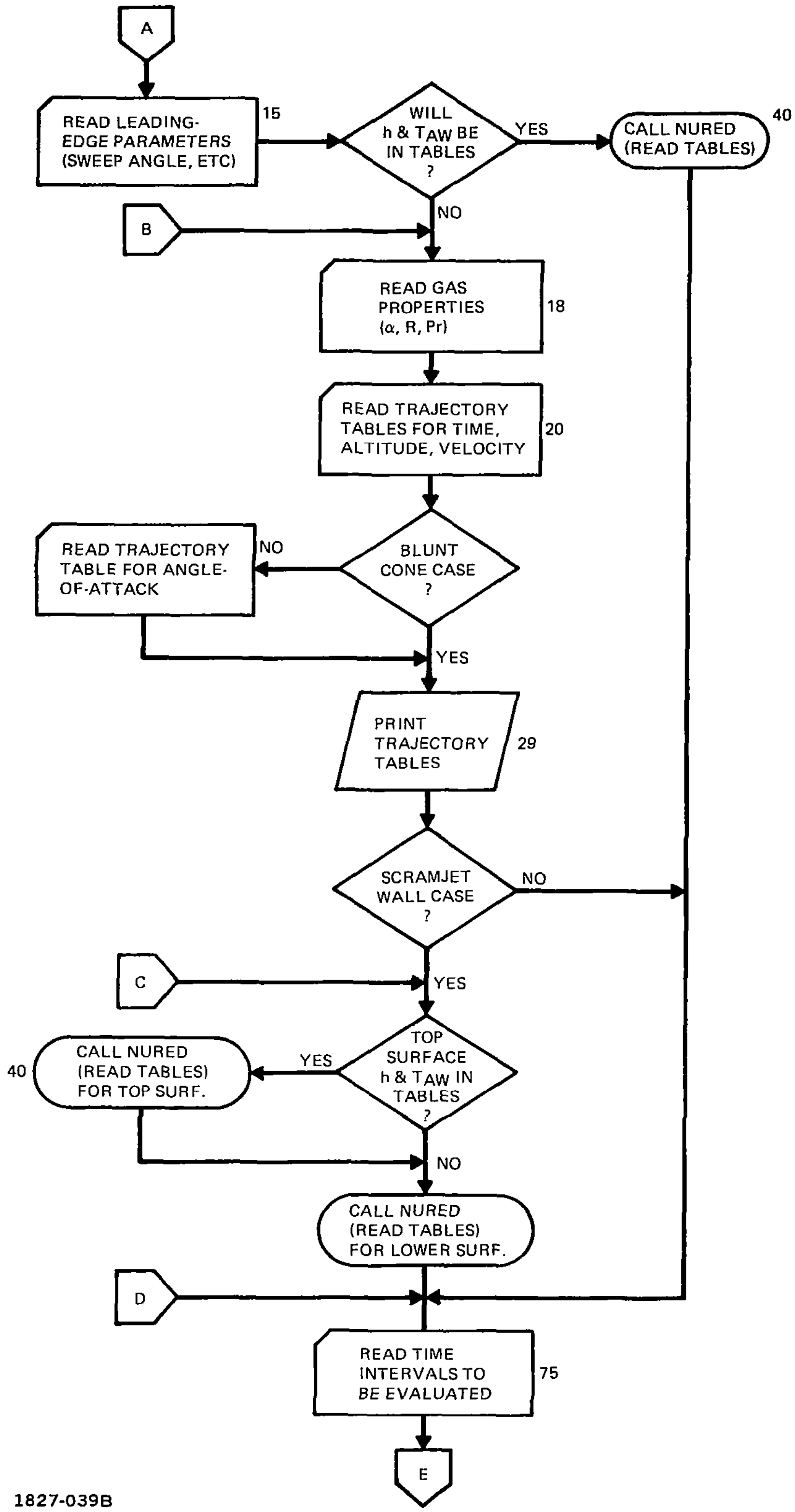
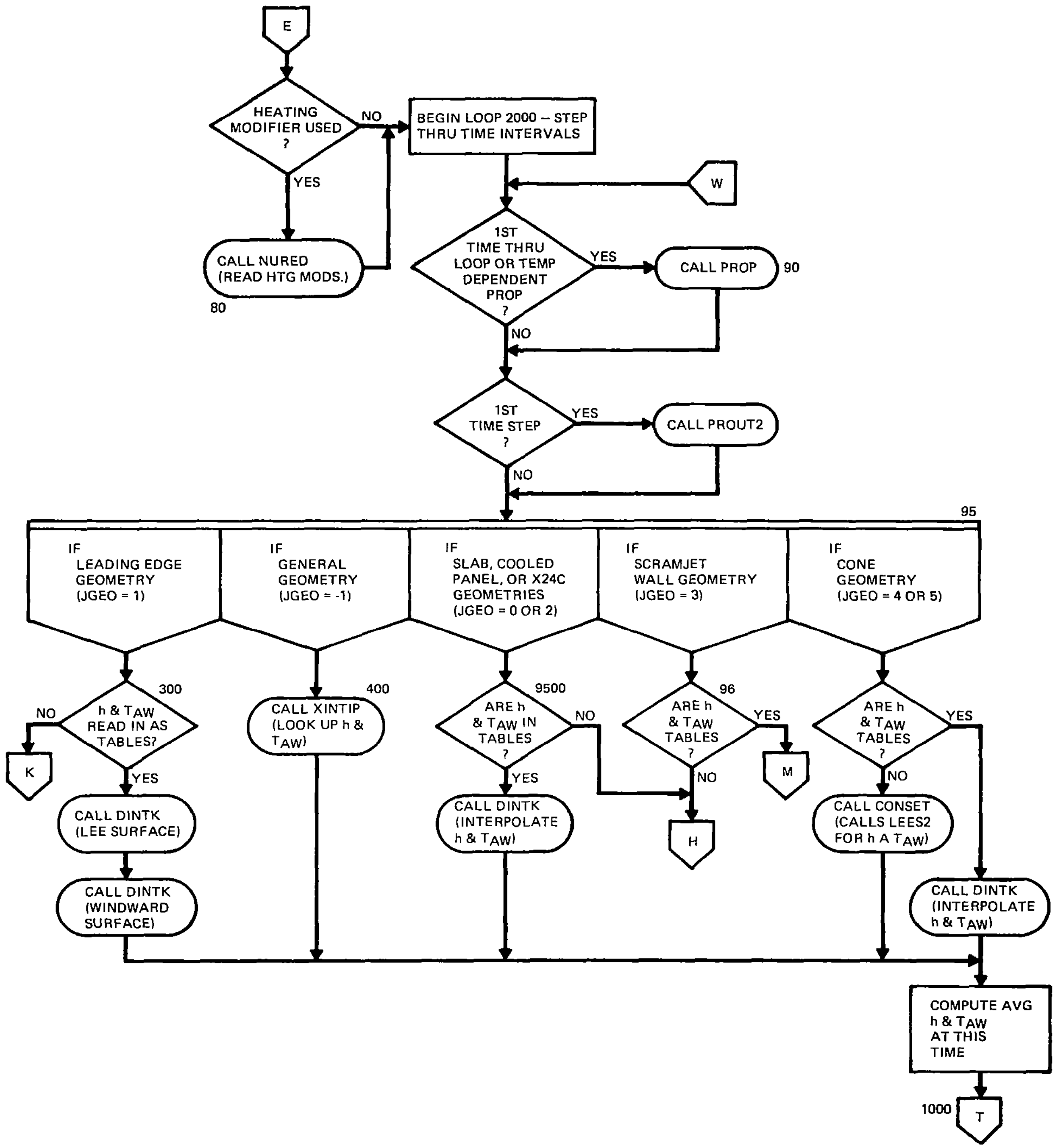
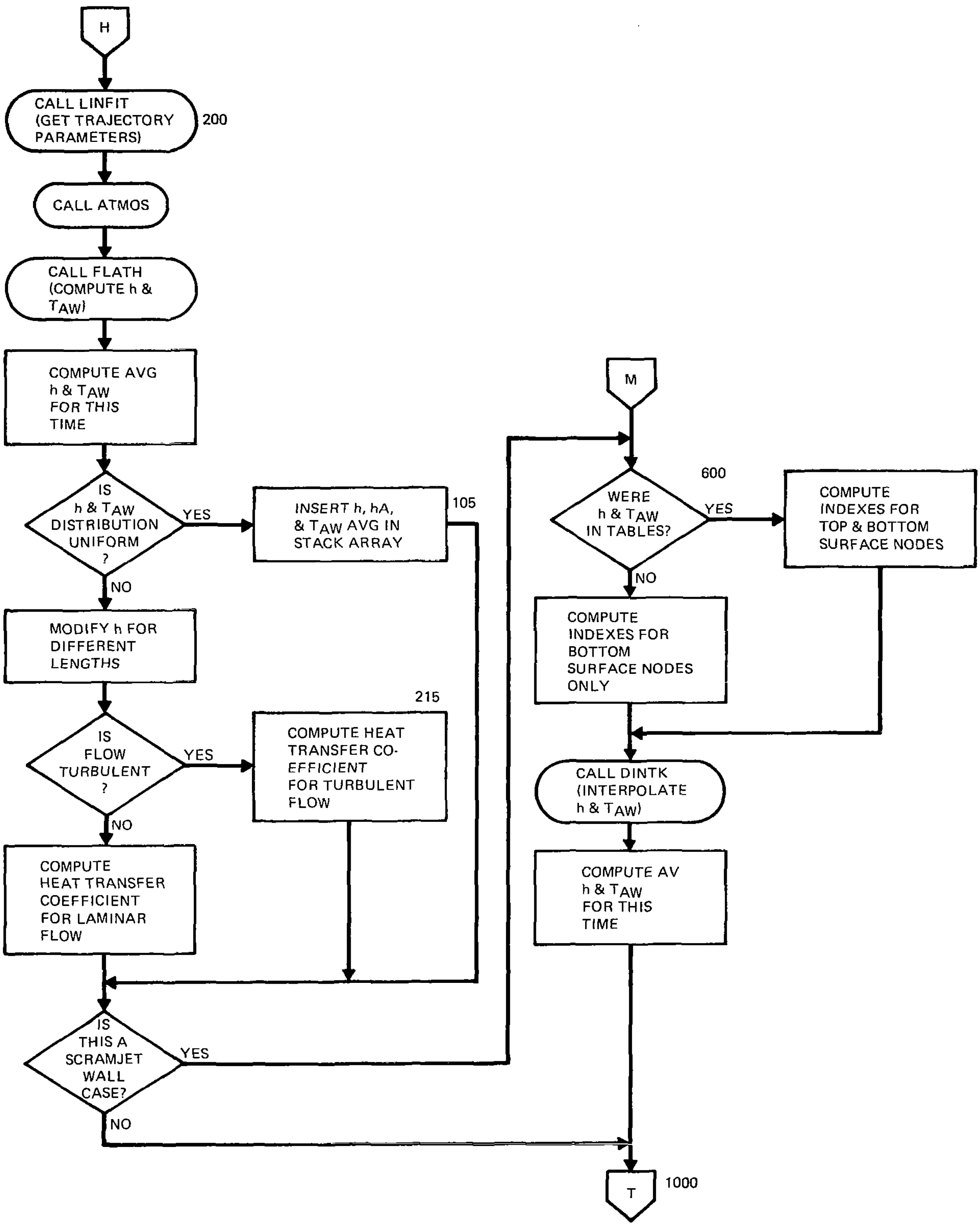


FIG A-4 SUBROUTINE OVLY 21 FLOW CHART (SHEET 2 OF 6)



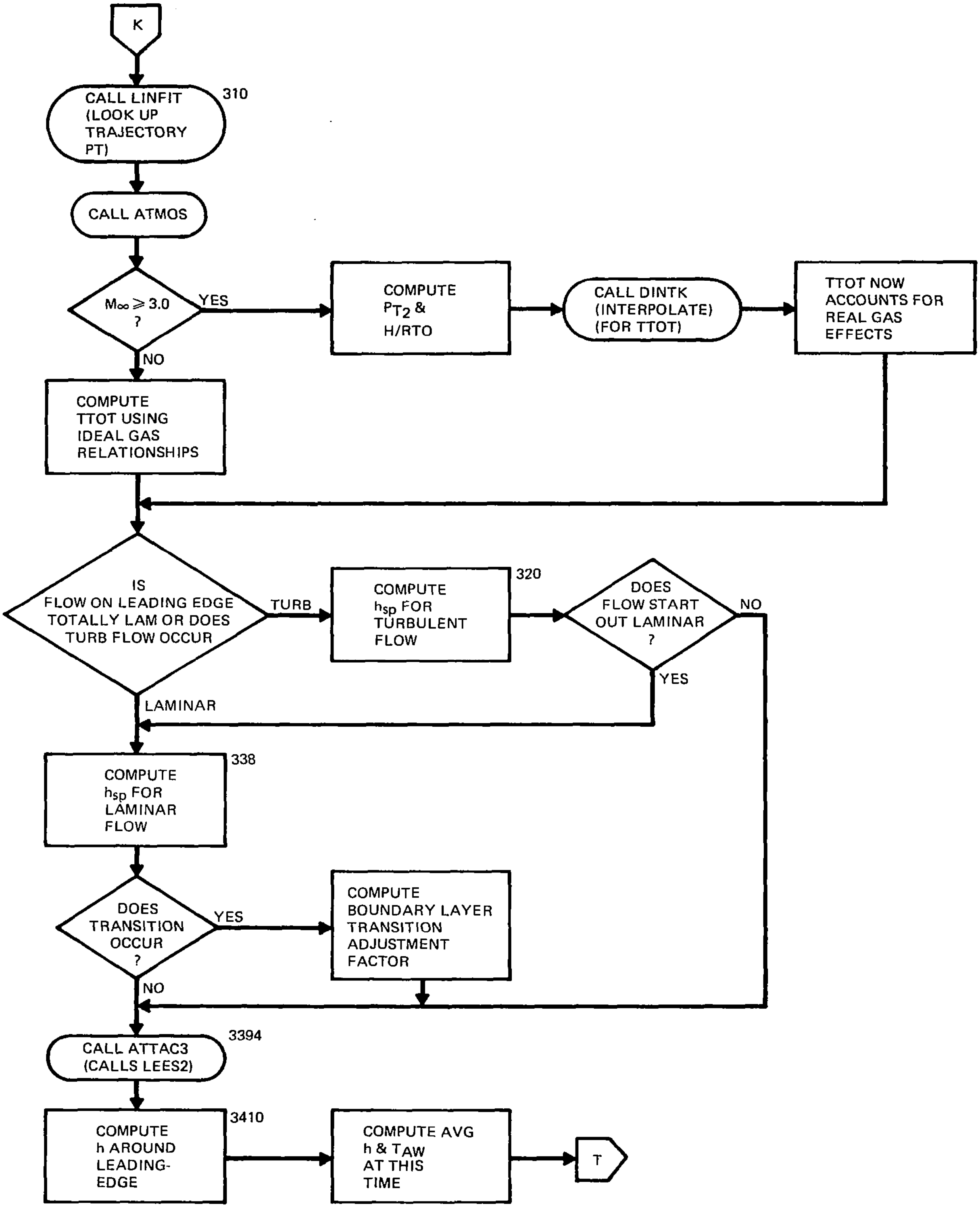
1827-040B

FIG. A-4 SUBROUTINE OVLY21 FLOW CHART (SHEET 3 OF 6)



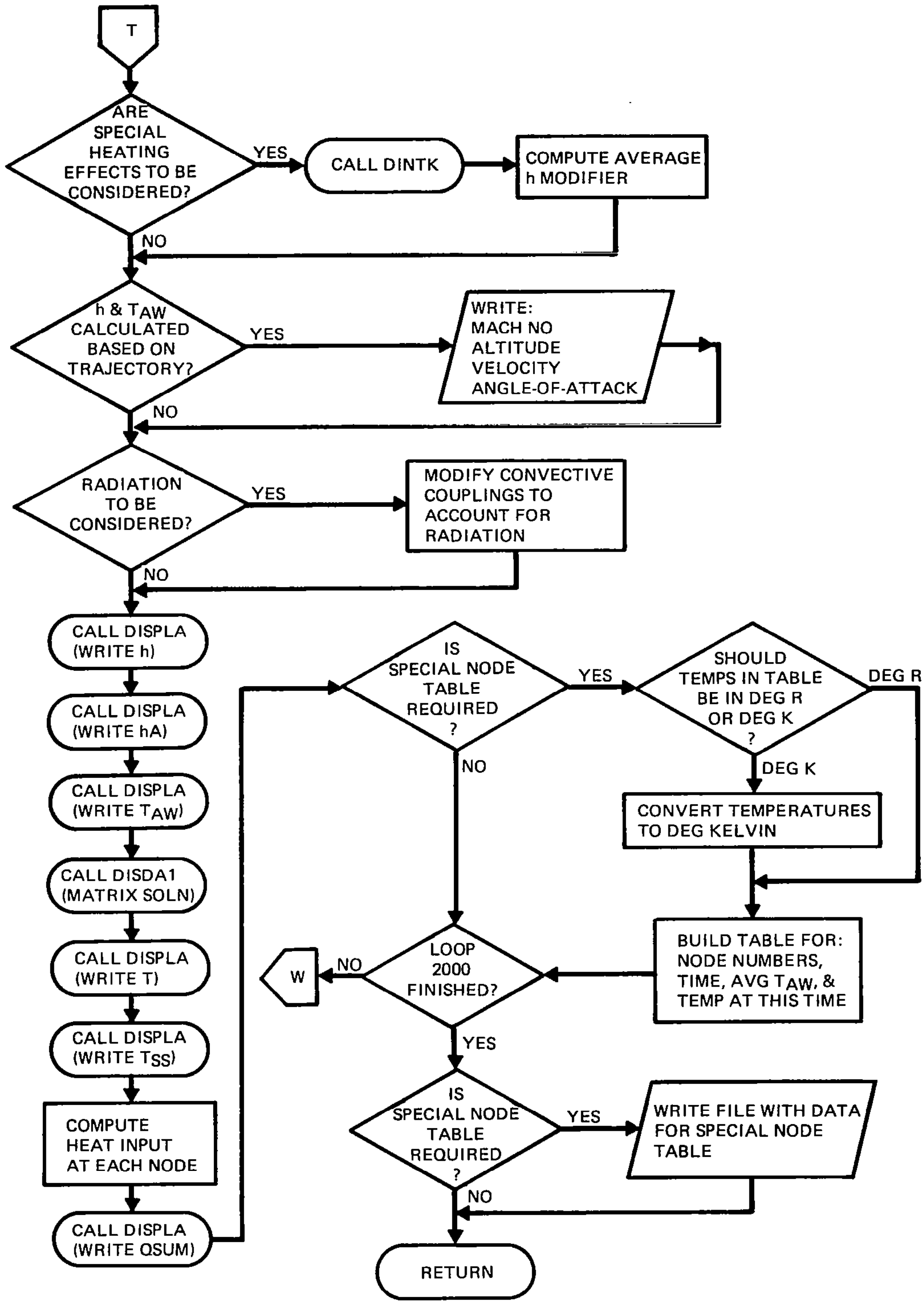
1827-041B

FIG A-4 SUBROUTINE OVLY 21 FLOW CHART (SHEET 4 OF 6)



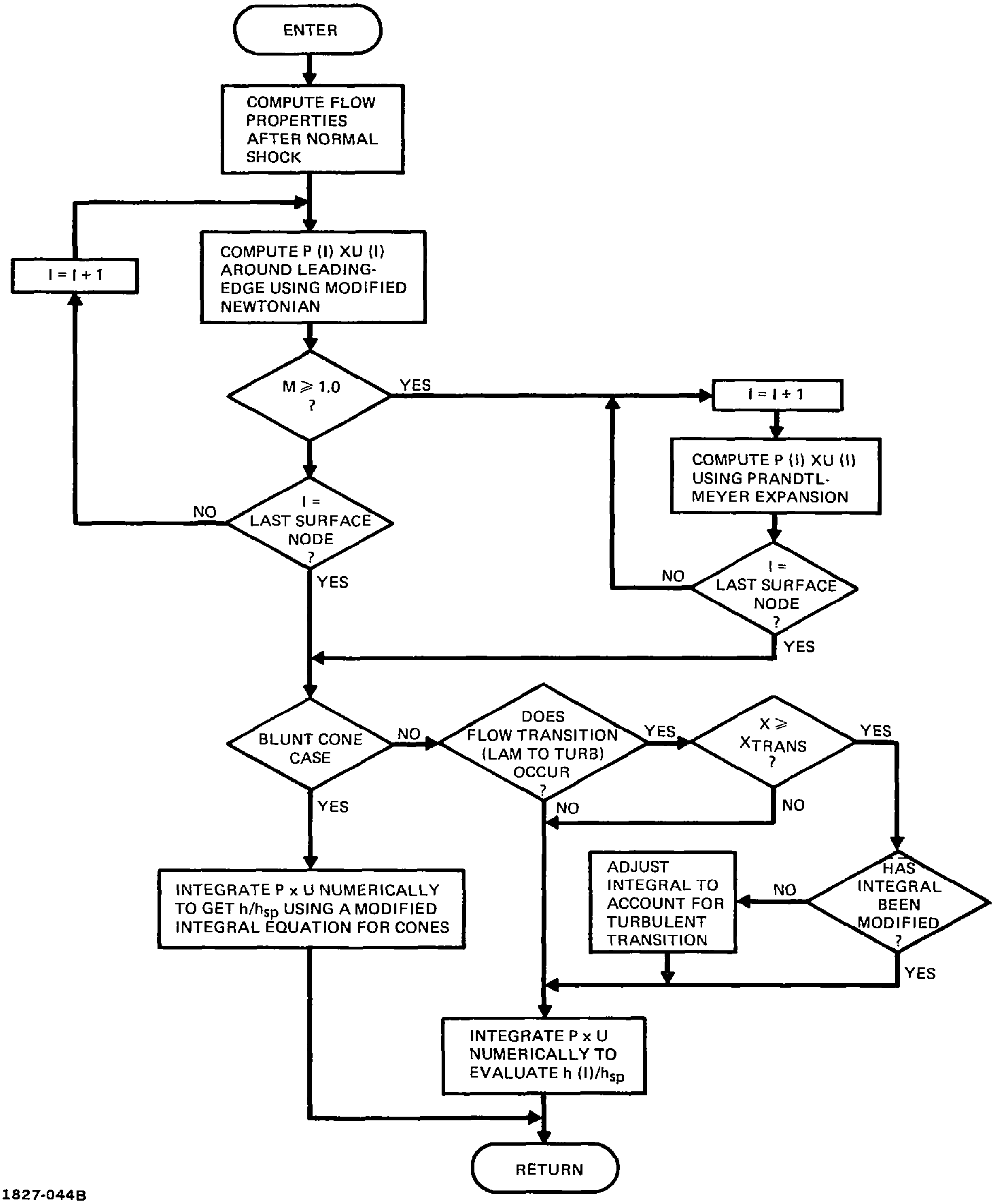
1827-042B

FIG. A-4 SUBROUTINE OVLY 21 FLOW CHART (SHEET 5 OF 6)



1827-043B

FIG. A-4 SUBROUTINE OVLY 21 FLOW CHART (SHEET 6 OF 6)



1827-044B

FIG A-5 SUBROUTINE LEES2 FLOW CHART

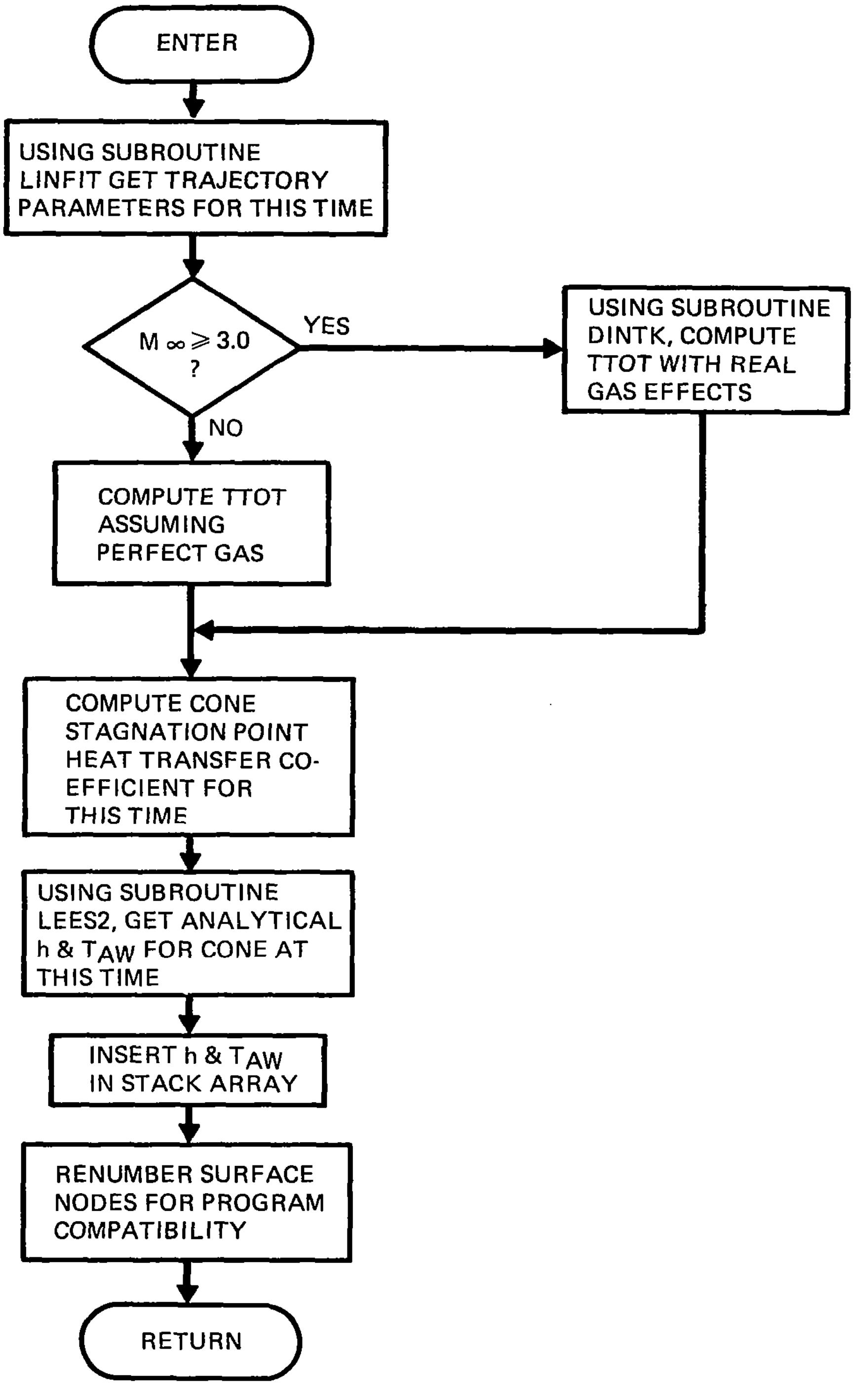


FIG. A-6 SUBROUTINE CONSET FLOW CHART

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16. Abstract

Under contract NAS1-13655, Grumman developed the computer code CAVE (Conduction Analysis via Eigenvalues), a convenient and efficient computer code for predicting two-dimensional temperature histories within thermal protection systems for hypersonic vehicles. NASA report CR-2897 describes fully the CAVE code and its operation.

Under the present contract the capabilities of CAVE have been enhanced by incorporation of the following features into the code: real-gas effects in the aerodynamic heating predictions, geometry and aerodynamic heating package for analyses of cone-shaped bodies, input option to change from laminar to turbulent heating predictions on leading edges, modification to account for reduction in adiabatic wall temperature with increase in leading edge sweep, geometry package for two-dimensional scramjet engine sidewall, with an option for heat transfer to external and internal surfaces, print-out modification to provide tables of select temperatures for plotting and storage, and modifications to the radiation calculation procedure to eliminate temperature oscillations induced by high heating rates.

This report describes these new features and is an addendum to report CR-2897.

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